# Introductory geology

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AMERICAN SCIENCE SERIES.

# INTRODUCTORY GEOLOGY

## A TEXT-BOOK FOR COLLEGES

BY

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AND
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*Heads of the Departments of Geology and Geography
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# PREFACE

This volume is an abbreviation and simplification of College Geology, published five years ago. Many technical details have been omitted, but the general purpose and scope of the volume is not altered fundamentally. It is intended to present an outline of the essential features of geology with as few technicalities as the nature of the subject permits. Part I deals with geological processes, and with the materials on which they operate, while the theme of Part II is historical geology. The effort has been to treat these topics in such a way as to give the student not merely an understanding of the subject, but also an understanding of the means by which the present status of the science has been reached.

The theoretical and interpretative elements which enter into the general conceptions of geology have been used freely, because they are regarded as an essential part of the evolution of the science, since they often help to clear and complete conceptions and to stimulate thought. The aim has been, however, to characterize hypothetical elements as such, and to avoid confusing the interpretations based on hypothesis with the statements of fact and established doctrines.

In many cases the topics discussed will be found to be presented in ways differing widely from those which have become familiar. In some cases, fundamentally new conceptions of familiar subjects are involved; in others, topics not usually discussed in text-books are stated with some fullness; and in still others, the emphasis is laid on points which have not commonly been brought into prominence. Whether the authors have been wise in departing to this extent from beaten paths, the users of the volume must decide.

The University of Chicago,
February, 1914.

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# GEOLOGY

## PART I

## THE MATERIALS OF THE EARTH AND PROCESSES WHICH AFFECT THEM

## CHAPTER I

### PRELIMINARY OUTLINE

*Geology is the history of the earth and its inhabitants.* It treats of the rocks and of the agencies and processes which have made them, and from the rocks, their structures, and their fossils, it attempts to make out the stages through which the earth and the life which has dwelt upon it, have passed.

**Subdivisions.** So broad a science has many subdivisions. *Cosmic* or *Astronomic Geology* treats of the outer relations of the earth; *Geognosy* treats of the materials of the earth, and its most important branch is *Petrology*, the science of rocks; *Structural Geology* deals with the arrangement of the rocks; *Dynamic Geology* deals with the forces involved in geologic processes; *Physiographic Geology* treats of the face of the earth, or topographic form; while *Paleontologic Geology*, or *Paleontology*, concerns itself with the fossils that have been preserved in the rocks, and with the faunas and floras that have lived in the past. The succession of events in the earth's history constitutes *Historical Geology*, which is worked out chiefly from the succession of beds of rock formed through the ages, and from the fossils they contain. Besides these general subdivisions, there are special applications of geologic knowledge which give rise to other terms. Thus *Economic Geology* is concerned with the industrial applications of geologic knowledge, and *Mining Geology*, a sub-section of economic geology, deals with the application of

geologic facts and principles to mining. Other similar subdivisions might be mentioned.

**Dominant processes.** Three sets of processes, still in operation on the surface of the earth, have made much of the record on which the science is based. These processes have been designated *diastrophism*, *vulcanism* (*volcanism*), and *gradation*. *Diastrophism* includes all movements of the outer parts of the lithosphere, whether slow or rapid, gentle or violent, slight or extensive. Many parts of the land, especially along coasts, are known to be sinking slowly relative to the sea-level, while other parts are known to be rising. The fact that sediments originally deposited beneath the sea now exist in some places at great elevations, together with the fact that certain areas which were once land are now beneath the sea, proves that similar changes have taken place in the past. Earthquakes are another illustration of diastrophism. *Vulcanism* includes all processes concerned with the movements of lava and other volcanic products, whether they issue at the surface or not. Vulcanism and diastrophism may be closely associated, for many local movements are associated with volcanic eruptions. *Gradation* includes all those processes which tend to bring the surface of the lithosphere to a common level. Gradational processes belong to two categories — those which level down, *degradation*, and those which level up, *aggradation*. The transportation of material from the land, whether by rain, rivers, glaciers, waves, or winds, is *degradation*, and the deposition of the sediment, whether on the land or in the sea, is *aggradation*. Degradation affects primarily the higher parts of the lithosphere, and aggradation the lower.

## THE EARTH IN THE SOLAR SYSTEM

Though supremely important to us, the earth is but one of the minor *planets* which revolve about the sun. Of the eight planets, four, Jupiter, Saturn, Uranus, and Neptune, are much larger than the earth, while three, Mercury, Venus, and Mars, are smaller. There are hundreds of *asteroids*, but all together they do not equal the mass of the smallest planet. Jupiter, the largest planet, has more than three hundred times the mass of the earth. The earth's position is in no sense distinguished, for it is neither the outermost nor the innermost, nor even the middle planet. In the inner group of four to which it belongs, it is the largest. Its average distance

from the sun is about 92.9 million miles, and its period of revolution, 365¼ days, is longer than that of any other one of the inner planets, and shorter than that of any one of the outer group. The orbit of the earth, like the orbits of the other planets, is an ellipse. The inclination of the earth's axis, nearly 23½°, is less than that of the axis of some planets, and more than that of others.

The earth is peculiar in having one unusually large *satellite*, which has a mass 1/81 of its own. The larger planets have several satellites whose combined mass exceeds that of the moon, and a few individual satellites may be larger than the moon; but no other is 1/81 of the size of the planet about which it revolves. The moon has played an important part in the history of the earth, for it is the chief cause of tides, and tides are efficient in the wear of the shores of the oceans and in the distribution of marine sediments. Tides probably have been important ever since the ocean came into existence.

The most important external relation of the earth is its dependence on the sun. Its mass is less than 1/300000 that of the sun, upon which it depends for nearly all its heat and light, and, through these, for nearly all of the activities that have determined its history. A little heat and light are received from other bodies, and an important source of energy is found in the interior of the earth itself; yet all of these are so far subordinate to the great flood of energy which comes from the sun, that they are quite insignificant. The dependence of the earth on the sun has been intimate throughout its past history, and its future is locked up with the destiny of that great luminary.

**Meteorites.** There are multitudes of small bodies, called meteorites, passing through space in varying directions and with varying velocities. Great numbers of these reach the earth daily as "shooting stars." Some *meteorites* revolve about the sun like planets, but some of them do not belong to the sun's family. Some consist almost wholly of metal, chiefly iron alloyed with a little nickel; some consist of metal and rock intimately mixed; and some consist wholly of rock. Since meteorites are thought to throw some light on the early history of the earth, they are of interest to the geologist. The amount of material added to the earth by the infall of meteorites is now slight compared with the whole body of the earth; but their contributions in the past may have been greater.

### THE GRAND DIVISIONS OF THE EARTH

**The constitution of the earth.** The materials of the earth into three grand divisions: (1) The *atmosphere*, (2) the *hydrosph* (water sphere), and (3) the *lithosphere* (rock sphere).

**The atmosphere.** Since the atmosphere is a part of the ear its history falls within the province of geology. It is an intim mixture of (1) all those substances that do not become liquid solid under the temperatures and pressures which exist at the eart surface, together with (2) such transient vapors as the vari liquid and solid substances of the earth throw off. The first the principal gases of the atmosphere, and consist of *nitrogen* ab 78 parts, *oxygen* about 21 parts, *carbon dioxide* about .03 pa together with small quantities of argon, and several other su stances. Chief among the second group is water vapor, wh varies greatly in amount from time to time and from place to pla Here, too, belong the gases which issue from volcanoes, and ma volatile organic substances. Dust and other matter suspended the air are regarded as impurities rather than constituents of atmosphere; but they are important because they affect the te perature and light of the air, and the condensation of its moistur

The mass of the atmosphere is estimated to be $^1/_{1200000}$ of total mass of the earth. It exerts a pressure of about fifteen pou per square inch at sea-level. Its density decreases upward, but actual height is not known. There is no direct evidence of existence above a few hundred miles, but there are theoreti grounds for believing that it reaches much greater heights.

*Geologic activity.* The atmosphere is the most mobile and act of the three great subdivisions of the earth. Its direct and indir effects on water and rocks are so great that it must be regarded one of the great agents of change in the earth's history. The fu tion of the atmosphere in sustaining life and promoting all t depends on life is obvious.

**The hydrosphere.** The water which lies upon the surface the solid earth is about $^1/_{4950}$ part of the earth's mass. Were solid part of the earth perfectly even, this amount of water wo make a universal ocean a little less than two miles deep; but ow to the unevenness of the lithosphere, most of the water is gathe in the great basins which affect its surface. These basins are connected, so that anything which changes the level of the wa in one, changes it in all.

The area of the oceans is estimated at 143,259,300 square miles, or about 72% of the earth's surface. The area of the true oceanic basins is only about 133,000,000 square miles, but the basins are somewhat more than full, and the ocean water overflows them, lapping up on the continental shelves to the extent of more than 10,000,000 square miles. If the uppermost 600 feet of the ocean water were removed, the true ocean basins would be just full. About 4/5 of the ocean has a depth of more than a mile, and more than half of it a depth exceeding two miles. Its greatest depth is nearly six miles, and its average about two and one-half miles.

The shallow waters which lie upon the continental shelves, or extend into the interiors of the continents, such as the Baltic Sea and Hudson Bay, are *epicontinental seas*, for they lie upon the low borders of the continental platforms. Those detached bodies of water which occupy deep depressions in the surface are to be regarded as true abysmal seas. Such, for example are the Mediterranean and Caribbean seas and the Gulf of Mexico, whose bottoms are as low as many parts of the true ocean basin itself. Besides the oceans, the hydrosphere includes all the water of streams and lakes, together with that which is in the pores and fissures of the lithosphere. The waters of the earth become a true hydro*sphere* only when the ground water is considered. All other waters of the earth are small in amount, compared with the ocean.

Of all geological agents operating on the surface, water is the most obvious and apparently the greatest. Through rainfall, surface streams, underground waters, and waves, water is constantly modifying the surface of the lithosphere, most obviously by carrying sediment from the higher land and depositing it in the various basins. The hydrosphere is the great agency for the degradation of the land and the building up of the basin bottoms. The beds of sediment which it lays down follow one another in orderly succession, each later one lying on an earlier. In this way, they form a time record. Relics (shells, bones, etc.) of the life of each age are embedded in the sediments, and record the history of life from age to age. The historical record of geology is dependent largely on the fact that the waters have buried, in systematic order, relics of the life of successive ages.

**The lithosphere.** The atmosphere and hydrosphere are outer shells, rather than true spheres, though both penetrate the lithosphere to some extent. The lithosphere, on the other hand, is an

oblate spheroid with a polar diameter of 7,899.7 miles, and equatorial diameter of about 26.8 miles more. Its equatorial c cumference is 24,902 miles, its meridional circumference 24,8 miles, and its surface area about 196,940,700 square miles. average specific gravity is about 5.57. The oblateness of t spheroid is the result of the rotation of the earth.

The earth is not a perfect spheroid. Its equatorial diamete are not exactly equal, and the continental protuberances are, on t average, some three miles above the bottoms of the oceans. T forces or agencies which produced the continental platforms a abysmal basins, and the great undulations, foldings, and volcan extrusions of both, are yet subjects of debate.

It is customary to look upon the continents as the great featur of the earth's surface, but in reality the oceanic depressions are t master feature. They exceed the continental protrusions in breadt and they are much farther below sea-level than the continents a above it. If the earth be regarded as a shrunken body, the settli of the ocean bottoms has doubtless been the greatest diastroph movement.

The following table shows the relative areas of the lithosphe above, below, and between certain levels.

| | Per cent |
|---|---|
| More than 6,000 feet above sea-level | 2.3 |
| Between sea-level and 6,000 feet above | 25.5 |
| Between sea-level and 6,000 feet below | 14.8 |
| Between 6,000 and 12,000 feet below sea-level | 14.8 |
| Between 12,000 and 18,000 feet below sea-level | 39.4 |
| Between 18,000 feet and 24,000 feet | 3.1 |

From these estimates it appears that if the surface of the lith sphere were graded to a common level by cutting away the cont nental platforms and dumping the material in the ocean basin bringing all to a common level, this level would be about 9,000 fe below sea-level. The continental platforms may be conceived rising from this common plane rather than from the sea-level.

The bottoms of the ocean basins have broad undulations rangin through many thousands of feet; but they have not those irreg larities of form that give variety to land surfaces. The ocean bo toms are also diversified by volcanic peaks, many of which const tute islands. From many of them, the solid surface slopes dow rapidly to abysmal depths. Many of the volcanic islands a

isolated mountains whose heights and slopes would seem extraordinary, if the ocean were removed.

The surface of the land is diversified similarly by broad undulations and volcanic peaks, as well as by narrower wrinklings and foldings of the crust, and all of these irregularities have been carved into varied and picturesque forms by erosion. In this respect, the land differs radically from the bed of the sea.

The outer part of the lithosphere is often called the *crust* of the earth. The old notion that it was the solid portion overlying a liquid part beneath is now generally abandoned. The crust is merely the outer, cooler portion of the lithosphere. Its thickness is undefined, but a shell several miles thick, and perhaps a few score miles, is generally meant when this term is used.

**Materials of the lithosphere.** *Mantle rock.* The great body of the lithosphere probably is composed of solid rock, but the solid rock is very generally covered by a layer of loose material such as soil, clay, sand, gravel, and broken rock, known collectively as *mantle rock.* The mantle rock of many places consists of the decayed products of underlying rocks. The upper part of mantle rock constantly is being blown away by wind and washed away by water, while the lower part is being renewed constantly by the

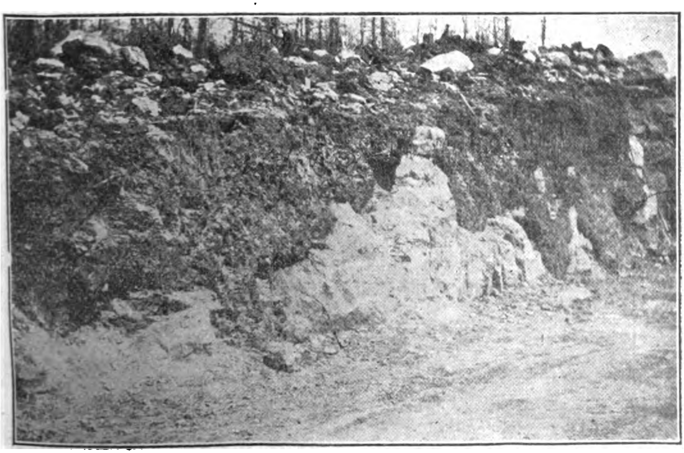


Fig. 1. Soil and subsoil arising from the decay of limestone resting on the uneven surface of the rock beneath. Southeastern Missouri. (Buckley.)

decay of the rock below. The mantle rock of some other areas, the northern part of North America and the northwestern part Europe, consists chiefly of an irregular sheet of commingled cla sand, gravel, and bowlders (*drift*) deposited by great glaciers, co parable to that which now covers Greenland. In still other plac especially along the flood plains of streams, the mantle rock consi of deposits made by rivers. Along the shores of lakes and se there are beach gravels and sands. The thickness of the man rock varies from almost nothing to hundreds of feet (Fig. 1).

*Solid rock.* Mantle rock is absent in some places, and th the surface of solid rock appears. It is common on the slopes steep-sided valleys and mountains, on the slopes of cliffs which fa seas or lakes, and in the channels of swift streams, especially wh there are falls or rapids. In all lands inhabited by civilized peop there are numerous wells and other excavations ranging from a f to several hundred feet in depth, and occasional wells and mi shafts go much deeper. In these, and even in many of the shallov excavations, solid rock is encountered, and in most regions exca tions as much as a few hundred feet deep reach it. We infer, the fore, that solid rock is nowhere far below the surface.

*Varieties of solid rock.* If the mantle rock were stripped fr the land, the solid part beneath would be found to be made up many kinds of rocks, all of which may be grouped into three class

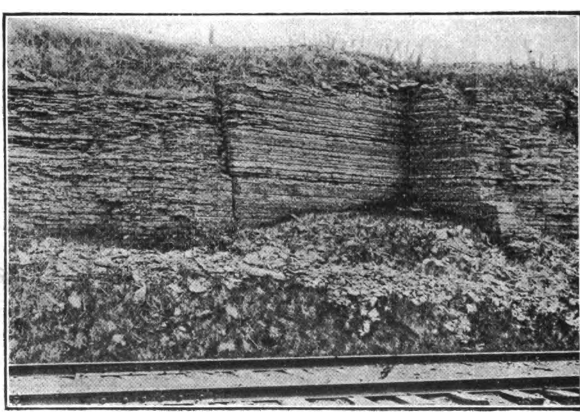


Fig. 2. Stratified rock. Trenton Limestone, Fort Snelling, Minn. (Calvin

By far the larger part of the land surface would be of *stratified* rock, and the remainder of rocks without distinct stratification. The latter are divided into two great groups, *igneous* rocks, and *metamorphic* rocks.

The essential feature of *stratified rock* (Fig. 2) is its arrangement in layers. The layers may be distinct or indistinct, and thick or thin. In many cases thick layers are made up of many thinner ones. In composition, most stratified rock corresponds somewhat closely with sediments now being carried from land and deposited in the sea; that is, these rocks are made up of gravel, sand, or mud, the particles of which are cemented together. The bedded arrangement of stratified rocks and of recent sediments is the same, and the

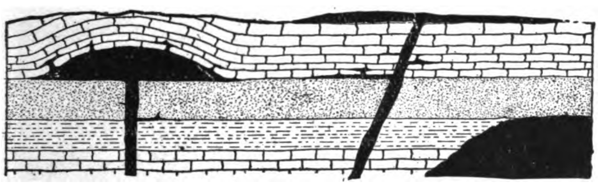


Fig. 3. Diagrammatic representation of the relations of igneous rock to stratified rock. The igneous rocks, represented in black, have been forced up from beneath.

markings on the surfaces of the layers, such as ripple-marks, rill-marks, wave-marks, etc., are identical. Furthermore, many of the stratified rocks of the land, like the recent sediments of the sea, contain the shells and skeletons of animals, and some of them the impressions of plants. Many of the relics of life found in the stratified rocks belonged to animals or plants which lived in salt water. Because of their structure, their composition, their distinctive markings, and the remains of life which they contain, it is confidently inferred that many, if not most, of the stratified rocks which lie beneath the mantle rock of the land originally were laid down in beds beneath the sea, and that the familiar processes of the present time furnish the key to their origin.

*Igneous rocks* may be defined as hardened lavas. They sustain various relations to stratified rocks, as illustrated by Fig. 3, in which some of the igneous rock is represented as lying beneath the stratified rock, some above it, and some interbedded with it, while some cuts across its layers. From these relations it is possible to tell some-

thing of the order in which the rocks were formed. Where stratified rocks are broken through by lavas, it is clear that the stratified rocks were formed first, and the lavas intruded later. Lava sheets intruded between beds of stratified rock can be told from those which flowed out on the surface and were subsequently buried, for

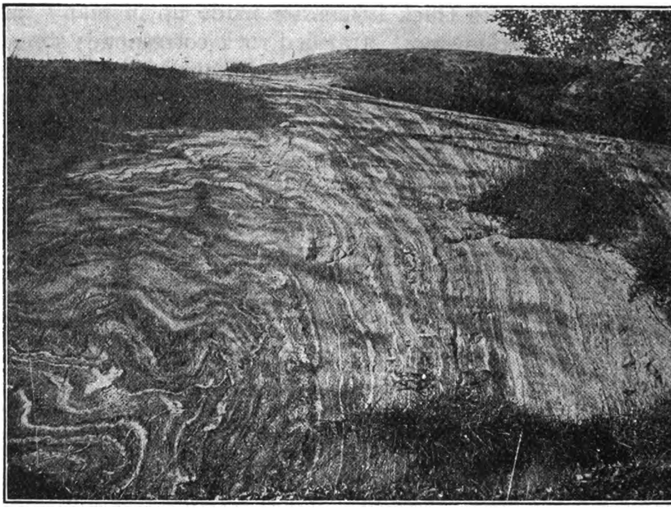


Fig. 4. Metamorphic rock. (Ells. Can. Geol. Surv.)

in the former case the sedimentary rocks, both above and below the igneous rock, were affected by the heat of the lava, while in the latter case only those below were so affected.

Most *metamorphic rock* has cleavage; that is, a tendency to break in one direction rather than in another. The cleavage of metamorphic rock may look much like stratification, but it is really very different. The tendency to break along certain planes is not due to the fact that the rock was deposited in layers originally, as in the case of stratified rock, but is the result of the changes which the rock has undergone since it was formed. The structure shown in Fig. 4 is known as *schistosity* — a structure characteristic of much metamorphic rock. Metamorphic rock may be derived from both igneous and sedimentary rocks.

More commonly than otherwise, metamorphic rocks lie beneath

sedimentary beds, or come to the surface from beneath them. Many of them are broken through by igneous rocks.

Concerning the great interior of the earth, little is known except by inference. From the weight of the earth,[1] it is inferred that its interior is much more dense than its surface. From its behavior under the attraction of other bodies, it is believed to be at least as rigid as steel. Its interior cannot, therefore, be liquid, in the usual sense of that term. From volcanoes, and from the temperatures in deep borings, it is inferred that the interior is very hot.

[1] The specific gravity of its outer portion is about 2.7, less than half that of the earth as a whole (5.57).

## CHAPTER II

### THE GEOLOGIC WORK OF THE ATMOSPHERE

Since the atmosphere is a part of the earth, its activities and its history are proper subjects of geologic study. As a part of geology, the study of the atmosphere is restricted, commonly, to its effects on the other parts of the earth. The origin and history of the atmosphere must, however, be considered, in any thoroughgoing history of the earth.

In the history of the earth, the atmosphere has played a part comparable to that of water, though its record is less clear. Its direct work is partly (1) mechanical and partly (2) chemical. Its indirect effects are even more important, for it furnishes the conditions under which (3) the sun produces its temperature effects, and (4) evaporation and precipitation take place. The atmosphere, too, furnishes the necessary conditions for plants and animals, and the important influences that spring from them.

#### MECHANICAL WORK

The mechanical work of the atmosphere is accomplished chiefly through its movements. A feeble breeze moves particles of dust, a wind of moderate velocity blows dry sand, and exceptionally strong winds move small pebbles.

The principal movement of the wind is horizontal; but every obstacle against which it blows deflects some of the air, and some of it is deflected upward. Furthermore, there are exceptional winds, in which the vertical element predominates. Particles of dust are caught by these upward currents, and carried to great heights. This facilitates their transportation great distances.

**Dust.**[1] Transportation of dust by the wind is nearly universal. No house, no room, and scarcely a drawer is so tightly closed but that dust enters, and the movements of dust in the open are much

[1] Udden, Jour. of Geol., Vol. II, pp. 318–331; also Pop. Sci. Mo., Sept., '96.

more considerable. The dustiness of the atmosphere in dry regions during wind-storms is familiar proof of the efficiency of the wind as a carrier of dust.

Under special circumstances, it is possible to determine roughly the distance and height to which dust is carried. In the great eruption of Krakatoa in 1883, large quantities of volcanic dust (pulverized lava) were shot up to great heights into the atmosphere. The coarser particles soon settled; but many of the finer ones, caught by the currents of the upper air, were carried around the earth in 15 days, and some of it traveled round the earth repeatedly. Its presence in the air was known by the historic red sunsets which it caused.[1]

Dust from volcanoes is shot into the atmosphere rather than picked up by it. Dust picked up by the wind is perhaps transported as widely, but, after settling, its point of origin is less readily determined. It would perhaps be an exaggeration to say that every

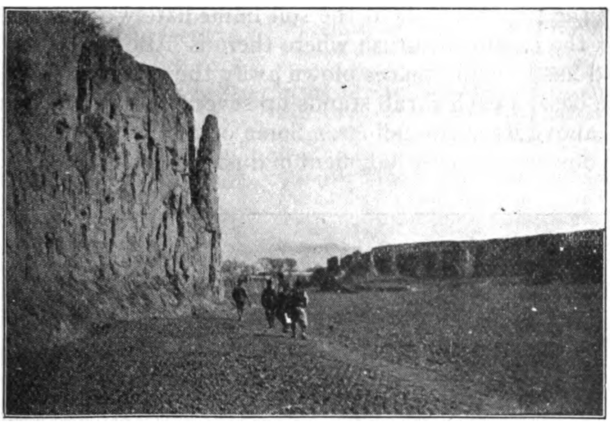


Fig. 5. Vertical face of loess near Huang-tu-Chai in northern Shan-si. The vertical faces are the result of erosion. (Willis, Carnegie Institution.)

square mile of land has particles of dust blown from every other square mile of dry land; but such a statement probably would involve much less exaggeration than might at first be supposed.

[1] A brief account of the influence of the dust on sunsets is found in Davis's Elementary Meteorology, pp. 85 and 119.

Extensive deposits of wind-blown dust are known. Considе able beds of volcanic dust, locally as much as 30 feet thick, a known in various parts of Kansas and Nebraska, hundreds of mil from the nearest volcanic vents. In some parts of China there an extensive earthy formation, the *loess* (Fig. 5), in some plac reaching a thickness of hundreds of feet, much of which is believ to have been deposited by the wind. The loess of other regio has been referred to the same origin, and much of it is quite certain eolian. From the flood plains of such rivers as the Missouri, clou of dust are swept up and out over the adjacent high lands at t present time, especially when the surface of the flood plain h become dry after floods. This dust is very like loess, if, indeed, is not loess.

The transportation of dust is important wherever strong win blow over dry surfaces free or nearly free of vegetation, and con posed of earthy or sandy matter. Its effects may be seen in suc regions as the sage-brush plains of western North America. Th roots of the sage-brush hold the soil immediately about them, bu between the clumps of brush where there is little other vegetatio the wind has in many places blown away the soil to such an exte that the base of each shrub stands up several inches, or even a fo or two, above its surroundings. Some of the mounds in this pos tion are due partly to the lodgment of dust about the bushes (Fig. 6

Fig. 6. Shows the effect of sage-brush or other similar vegetation in holdin sand or earth, or in causing its lodgment, in dry regions.

Since dust is carried to a considerable extent in the upper air, its movements and its deposition are affected but little by obstacles on the surface of the land, and when it falls it is spread more or less uniformly over the surface.

Much of the dust transported by the wind is carried out over seas or lakes and falls into them, causing sedimentation over their bottoms. No determinations of the amount of dust blown into the sea have been made, but it is safe to say that, if such determination were possible, the result would be surprising.

**Sand.** Winds do not commonly lift sand far above the surface of the land, and its movement is therefore interfered with seriously by surface obstacles. A shrub, a fence, a building, or even a stone may occasion the lodgment of sand in quantity, though it has little effect on dust. If the obstacle which causes the lodgment of sand presents a surface which the wind cannot penetrate, such as a wall, sand is dropped abundantly both on its windward and leeward sides (Fig. 7); but if it be penetrable, like an open fence, the lodgment takes place chiefly to leeward. In cultivated regions, cases are known where, in a few weeks of dry weather, sand has drifted into lanes in the lee of hedges to the depth of two or three feet, making it difficult for vehicles to pass.

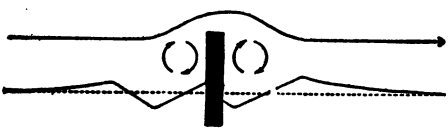


Fig. 7. Diagram to illustrate the effect of an obstacle on the transportation and deposition of sand. The direction of the wind is indicated by the upper arrow. The lower arrows represent the direction of eddies in the air, caused by the obstruction. If the surface in which the obstacle was set was originally flat (dotted line), the sand would tend to be piled up on either side at a little distance from it, but more to leeward. At the same time, a depression would be hollowed out near the obstacle itself on either side. (After Cornish.)

*Dunes.*[1] In contrast with eolian dust, much eolian sand is aggregated into mounds and ridges called *dunes*. Some dunes are 200 or 300 feet high, but many more are no more than 10 or 20 feet in height. The shape of dunes depends, among other things, on the extent and form of the area furnishing the sand, the strength and direction of the wind, and the shape of the obstacles which occasion the lodgment. The shapes of the cross-sections of dunes are influenced by the strength and constancy of the winds. With constant

[1] Geog. Jour., Apr., 1910, p. 379.

winds and abundant drifting sand, dunes are steep on the lee side (*bc*, Fig. 8), where the angle of slope rarely exceeds 25°. Under the same conditions, the windward slope is relatively gentle (*ab*).

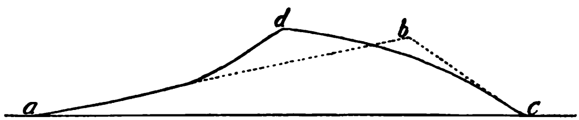



Fig. 8. Section of a dune showing, by the dotted line, the steep leeward (*bc*) and gentler windward (*ab*) slope. By reversal of the wind, the cross-section may be altered to the form shown by the line *adc*. (Cornish.)

If the winds are variable, so that the windward slope of one time becomes the leeward slope of another, and vice versa, this form is not preserved. By reversal of the wind, the section *abc* may be changed to *adc*. Where the winds erode (scour) more than they deposit, other profiles are developed. The erosion profiles may be

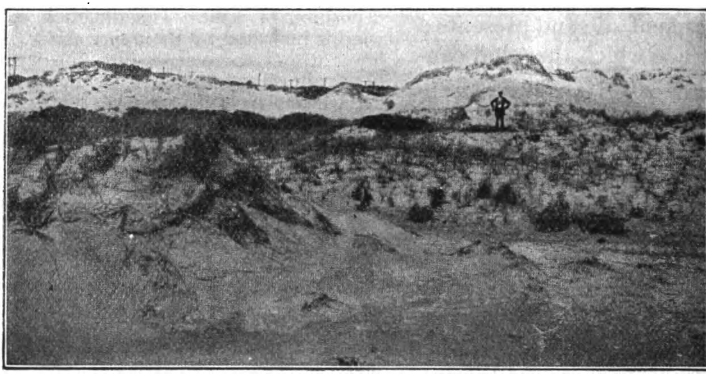


Fig. 9. Dunes at Longport, coast of New Jersey, showing the irregular forms developed by winds which erode.

very irregular if the dunes are partially covered with vegetation (Fig. 9).

*Topography of dune areas.* From what has been said, it is clear that the topography of dune regions varies widely, but it is always distinctive. Where the dunes take the form of ridges (Fig. 1, Pl. I), the ridges may be of essentially uniform height and width for con-

siderable distances. If there are parallel ridges, they may be separated by trough-like depressions. Where dunes assume the form of hillocks (Figs. 2 and 3, Pl. I) rather than ridges, the topography is even more distinctive. In some regions depressions (basins) are associated with the dune hillocks. In some places they are hardly less notable than the dunes themselves.

### THE TOPOGRAPHIC MAP

Since dunes as well as other topographic features are conveniently represented on contour maps, and since such maps will be used frequently in the following pages, a general explanation of them is here introduced.

"The features represented on the topographic map are of three distinct kinds: (1) inequalities of surface, called *relief*, as plains, plateaus, valleys, hills, and

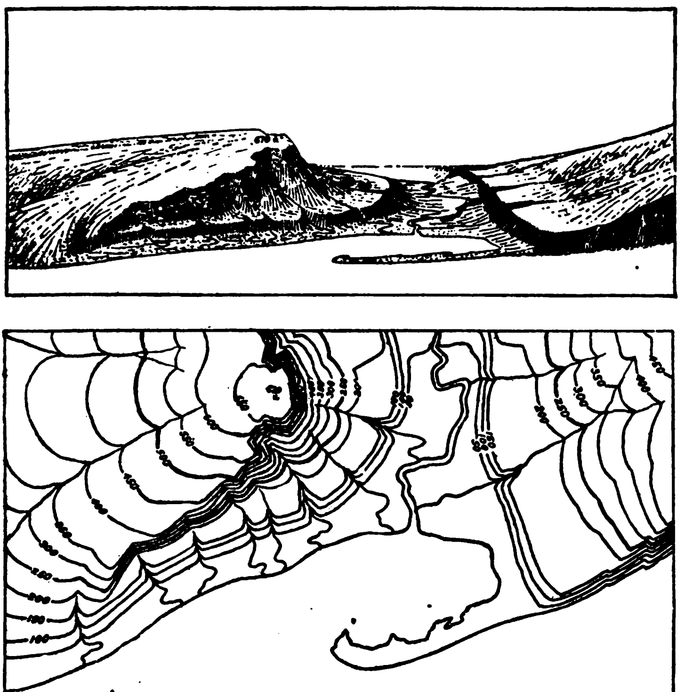


Fig. 10. Sketch and map of the same area, to illustrate the representation of topography by means of contour lines. (U. S. Geol. Surv.)

mountains; (2) distribution of water, called *drainage*, as streams, lakes, and swamps; (3) the works of man, called *culture*, as roads, railroads, boundaries, villages, and cities.

"**Relief.** All elevations are measured from mean sea-level. The heights of many points are accurately determined, and those which are most important are given on the map in figures. It is desirable, however, to give the elevation of all parts of the area mapped, to delineate the horizontal outline, or contour, of all slopes, and to indicate their grade or degree of steepness. This is done by lines connecting points of equal elevation above mean sea-level, the lines being drawn at regular vertical intervals. These lines are called *contours*, and the uniform vertical space between two contours is called the *contour interval*. On the maps of the United States Geological Survey the contours and elevations are printed in brown (see Pl. I).

"The manner in which contours express elevation, form, and grade is shown in the preceding sketch and corresponding contour map, Fig. 10.

"The sketch represents a river valley between two hills. In the foreground is the sea, with a bay which is partly closed by a hooked sand-bar. On each side of the valley is a terrace. From the terrace on the right a hill rises gradually, while from that on the left the ground ascends steeply in a precipice. Contrasted with this precipice is the gentle descent of the slope at the left. In the map each of these features is indicated, directly beneath its position in the sketch, by contours. The following explanation may make clearer the manner in which contours delineate elevation, form, and grade:

"1. A contour indicates approximately a certain height above sea-level. In this illustration the contour interval is 50 feet; therefore the contours are drawn at 50, 100, 150, 200 feet, and so on, above sea-level. Along the contour at 250 feet lie all points of the surface 250 feet above sea; along the contour at 200 feet, all points that are 200 feet above sea; and so on. In the space between any two contours are found elevations above the lower and below the higher contour. Thus the contour at 150 feet falls just below the edge of the terrace, while that at 200 feet lies above the terrace; therefore all points on the terrace are shown to be more than 150 but less than 200 feet above sea. The summit of the higher hill is stated to be 670 feet above sea; accordingly the contour at 650 feet surrounds it. In this illustration nearly all the contours are numbered. Where this is not possible, certain contours — say every fifth one — are accentuated and numbered; the heights of others may then be ascertained by counting up or down from a numbered contour.

"2. Contours define the forms of slopes. Since contours are continuous horizontal lines conforming to the surface of the ground, they wind smoothly about smooth surfaces, recede into all re-entrant angles of ravines, and project in passing about prominences. The relations of contour curves and angles to forms of the landscape can be traced in the map and sketch.

"3. Contours show the approximate grade of any slope. The vertical space between two contours is the same, whether they lie along a cliff or on a gentle slope; but to rise a given height on a gentle slope one must go farther along the surface than on a steep slope, and therefore contours are far apart on gentle slopes and near together on steep ones.

"For a flat or gently undulating country a small contour interval is used; for a steep or mountainous country a large interval is necessary. The smallest

interval used on the atlas sheets of the Geological Survey is 5 feet. This is used for regions like the Mississippi delta and the Dismal Swamp. In mapping great mountain masses, like those in Colorado, the interval may be 250 feet. For intermediate relief contour intervals of 10, 20, 25, 50, and 100 feet are used.

"**Drainage.** Watercourses are indicated by blue lines. If the streams flow the year round the line is drawn unbroken, but if the channel is dry a part of the year the line is broken or dotted. Where a stream sinks and reappears at the surface, the supposed underground course is shown by a broken blue line. Lakes, marshes, and other bodies of water are also shown in blue, by appropriate conventional signs.

"**Culture.** The works of man, such as roads, railroads, and towns, together with boundaries of townships, counties, and states, and artificial details, are printed in black." From folio preface, U. S. Geol. Surv.

**Explanation of Plate I.** In Fig. 1, Plate I (Five Mile Beach, 8 miles northeast of Cape May, N. J.), the contour interval is 10 feet. There is here but one contour line (the 10-foot contour), though this appears in several places. Since this line connects places 10 feet above sea-level, all places between it and the sea (or marsh) are less than 10 feet above the water, while all places within the lines have an elevation of more than 10 feet. None of them reaches an elevation of 20 feet, since a 20-foot contour does not appear. It will be seen that some of the elevations in Fig. 1 are elongate, while others have the forms of mounds. (From Cape May, N. J., Sheet, U. S. Geol. Surv.)

Fig. 2 shows dune topography along the Arkansas River in Kansas (Larned Sheet), and Fig. 3, dune topography in Nebraska (Camp Clarke Sheet), not in immediate association with a valley or shore. In Fig. 2 the contour interval is 20 feet. All the small hillocks southeast of the river are dunes. Some of them are represented by one contour, and some by two. In Fig. 3, where the contour interval is also 20 feet, there are, besides the numerous hillocks, several depressions (basins). These are represented by hachures inside the contour lines. In some cases there are intermittent lakes (blue) in the depressions. There are two depression contours (4280 and 4260) within the contour of 4300, near Spring Lake. The bottom of the depression is therefore lower than 4260, but not so low as 4240.

*Migration of dunes.*[1] By the transfer of sand from its windward to its leeward side, a dune is moved from one place to another, though continuing to be made up, in large part, of the same sand. In their migration, dunes may invade fertile lands, causing so great loss that means are devised for stopping them. The simplest method is to help vegetation to get a foothold in the sand. The effect of the vegetation is to pin the sand down.

Where dunes migrate into a timbered region, they bury and kill the trees (Fig. 11). On the coast of Prussia a tall pine forest, covering hundreds of acres, was destroyed between 1804 and 1827. At some points in New Jersey orchards have been so far buried within the lifetime of their owners that only the tops of the highest trees

[1] Beadnell, Sand Dunes of the Libyan Desert, Geog. Jour., XXXV, 379, 1910.

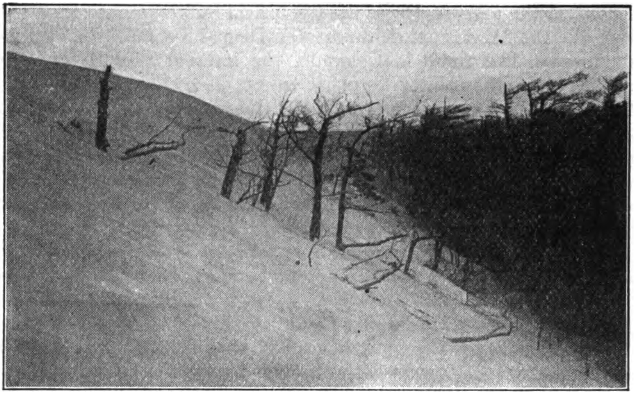


Fig. 11. Lee side of a sand dune, Cape Henry, Va. The dune is advancing on a forest and burying the trees. (Hitchcock.)

are exposed. Trees and other objects once buried may be discovered again by farther migration of the sand [1] (Fig. 12).

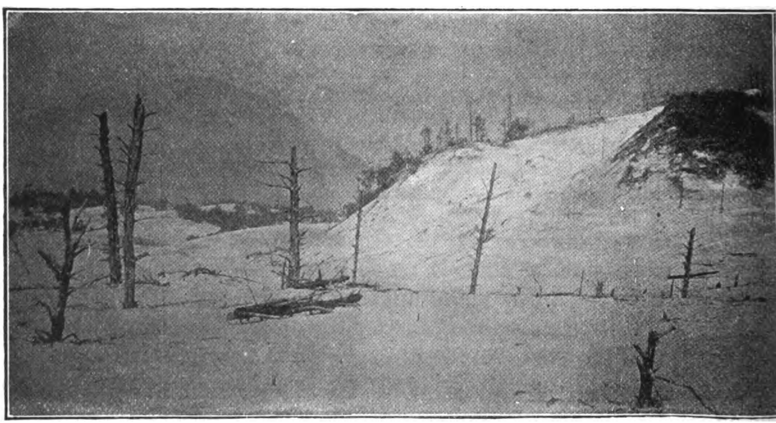


Fig. 12. A resurrected forest. After burying and killing the forest, the sand was blown away, exposing the dead trees. (Myers.)

[1] Cowles. The Ecological Relations of the Vegetation of the Sand Dunes of Lake Michigan. Botanical Gazette, Vol. XXVII, 1899. An excellent study of the relations of sand dunes and vegetation.

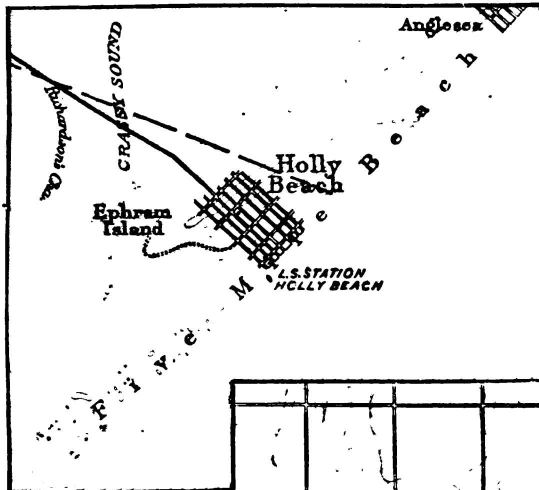



FIG. 1.—Dunes on coast of New Jersey. Scale, about 1 mile per inch. Contour interval, 10 feet. (Cape May Sheet, U. S, Geol. Surv.)

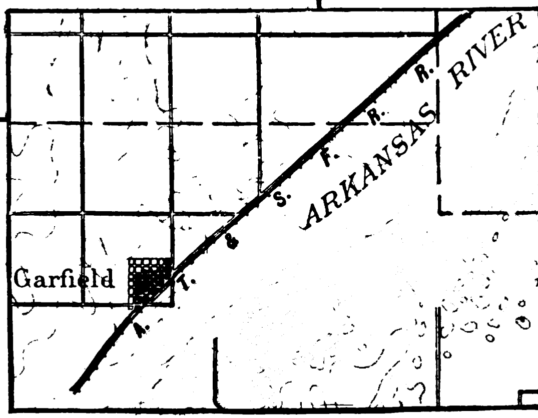



FIG. 2.—Dunes along Arkansas River in Kansas. Scale, about 2 miles per inch. Contour interval, 20 feet. (Larned Sheet, U. S. Geol. Surv.)

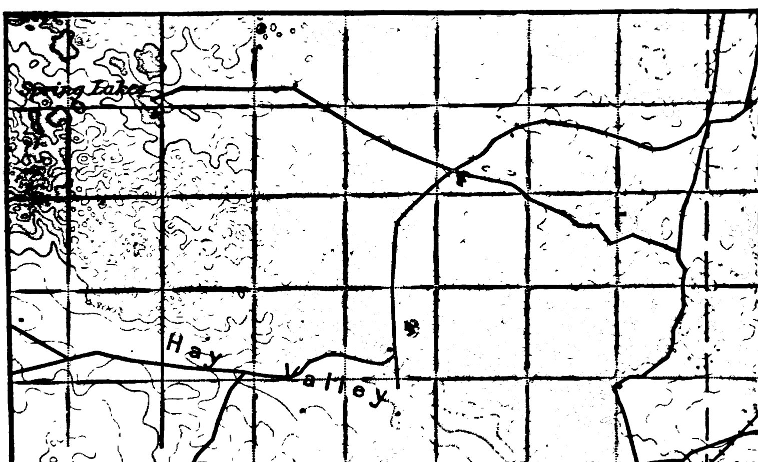
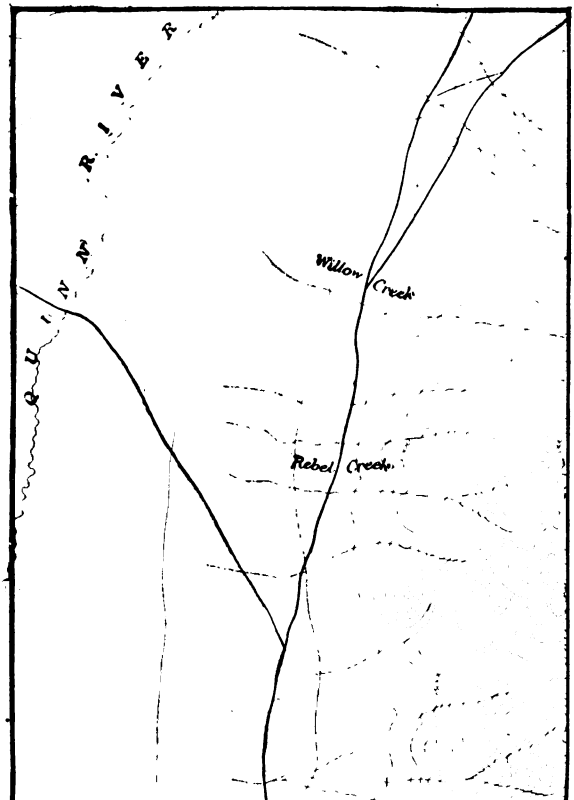



FIG. 3.—Dunes in plains of Nebraska. Scale, about 2 miles per inch. Contour interval, 20 feet. (Camp Clarke Sheet, U. S. Geol. Surv.)

PLATE II




Streams disappearing in the sand, gravel, etc., at the base of mountains in an arid region. Scale, about 4 miles per inch. Contour interval, 200 feet. (Paradise, Nev., Sheet, U. S. Geol. Surv.)

*Distribution of dunes.* Dunes are likely to be formed wherever dry sand is exposed to the wind. They are especially characteristic of the dry sandy shores of lakes and seas, of sandy valleys, and of arid, sandy plains. Along coasts, dunes are developed extensively only where the prevailing winds are on shore. Thus about Lake Michigan, where the prevailing winds are from the west, dunes are abundant and large on the east shore, and few and small on the west. Along valleys, dunes are most numerous on the far side as the prevailing winds blow. The dunes may be in the valleys, but in quite as many cases the sand is blown up out of the valley, and the dunes are on the bluffs above. Dunes probably reach their greatest development in the Sahara, but they are conspicuous in other arid sandy tracts, as in some parts of western Kansas and Nebraska, and in parts of Wyoming.

Eolian sand is not all piled up into dunes. It may be spread somewhat evenly over the surface where it lodges. Eolian sand is much more widespread than dunes are.

*Wind-ripples.* The surface of the dry sand over which the wind has blown for a few hours is likely to be marked with ripples (Fig. 13). While the ripples are, as a rule, but a fraction of an inch high, they throw light on the origin of the great dune ridges. If

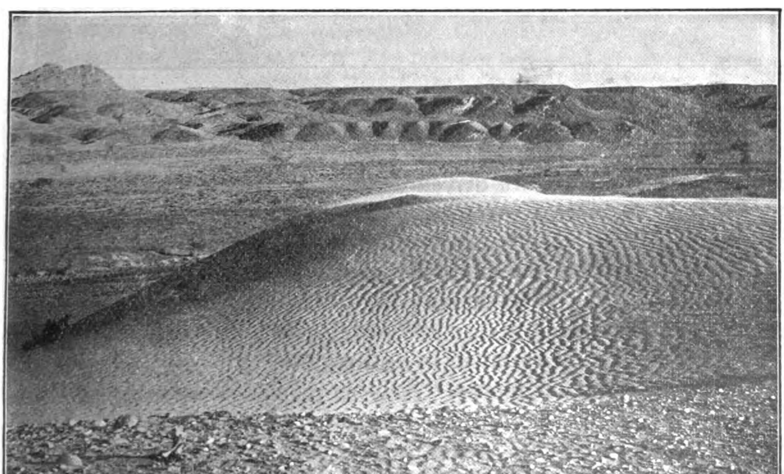


Fig. 13. A ripple-marked sand dune in a western valley. (U. S. Geol. Surv.)

the ripples be watched closely as the wind blows, they are found to shift their position gradually. Sand is blown up the gentler windward slope to the crest of the ridge, and falls down on the other side. Wear on the windward side may be about equal to deposition on the leeward, and the result is the orderly progression of the ripples in the direction in which the wind is blowing, just as in the case of dune ridges.

**Abrasion.** While the effect of the wind on sandy and dusty surfaces is considerable, its effect on solid rock is slight, except

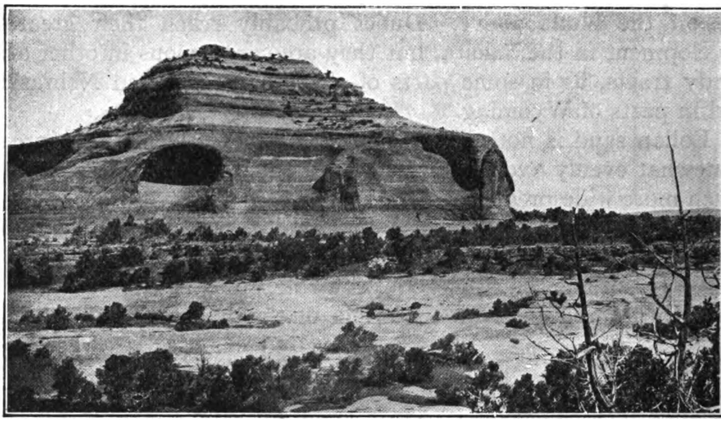


Fig. 14. Wind erosion. Cave rocks near Sierra La Sal, in Dry Valley, Utah. (Cross, U. S. Geol. Surv.)

where sand and dust are driven against it. Rock worn by wind-blown sand acquires a surface peculiar to the agent accomplishing the work. If the rock is made up of laminæ of unequal hardness, the blown sand digs out the softer ones, leaving the harder ones to project as ridges. The sculpturing thus effected on projecting masses of rock is picturesque and striking in some cases (Figs. 14 and 15), and is most common in arid regions.

**Effect of wind on plants.** Another effect of strong winds is seen in the uprooting of trees. The uprooting disturbs the surface, making the loose earth more readily accessible to wind and water. Organisms of various sorts (certain types of seeds, germs, etc.), as well as dust and sand, are transported far by wind.

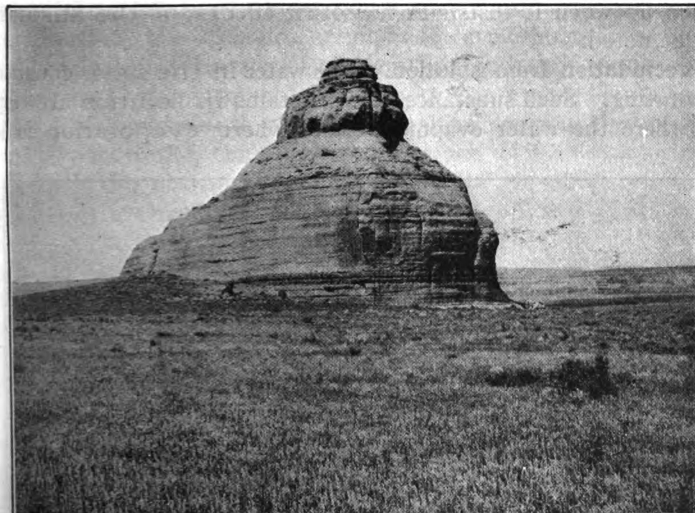


Fig. 15. Wind erosion. Casa Colorado, Dry Valley, Utah, between Abajo and La Sal Mountains. La Plata (Jurassic) sandstone. (Cross, U. S. Geol. Surv.)

**Indirect effects.** Other dynamic processes are called into being by the atmosphere. Winds generate both waves and currents, which are effective agents in geologic work. The results of their activities are discussed elsewhere.

### CHEMICAL WORK

The chemical work of the atmosphere is accomplished principally in connection with water. Dry air has little chemical effect on rocks or soils. The important chemical changes wrought by the atmosphere are *oxidation*, *carbonation*, and *hydration*. Oxidation, as used in this connection, is the union of oxygen with some constituent of the rock, forming an oxide. Carbonation is a union of carbon dioxide of the air with constituents of the rock, forming carbonates. Hydration, similarly, is the union of water with constituents of the rock. Oxidation and hydration may go on at the same time. Thus when iron rusts, oxygen and water both enter into combination with the iron. In most cases these chemical changes result in breaking up the rock, much as steel or iron is

broken up when it rusts. A few other effects of the atmosphere may be noted.

**Precipitation from solution.** The water in the soil is constantly evaporating. Such substances as it contains in solution are deposited where the water evaporates, and where evaporation is long

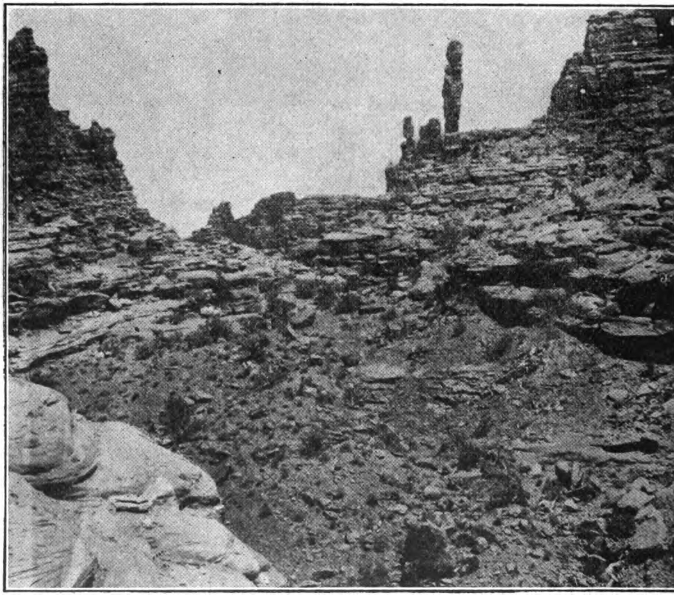


Fig. 16. Erosional forms characteristic of dry regions where erosion by the wind is effective. Fissure Canyon, north slope of the La Sal Mountains, Utah. The rock is Permian. (Cross, U. S. Geol. Surv.)

continued, without re-solution of the substances deposited, the surface becomes coated with an efflorescence of mineral matter. An illustration is found in the alkali plains of certain areas in the western part of the United States. Certain substances, deposited when the water which held them in solution is evaporated, coat the pebbles and stones of some arid plains. In some places gravel is thus cemented into conglomerate.

**Conditions favorable.** Conditions are not everywhere equally favorable for the chemical work of the atmosphere. Since high

temperatures facilitate chemical action, rocks are more readily decomposed by the chemical action of the atmosphere in warm than in cold regions. Changes of temperature tend to disrupt rock, and thus increase the amount of rock-surface exposed to chemical change. The elements of the atmosphere are much more active chemically in moist than in dry regions.

Though the chemical changes effected by the air are slow, their importance in the course of the earth's long history has been very great. The amount of rock which has been thus disintegrated probably far exceeds all that is now above the sea.

### THE ATMOSPHERE AS A CONDITIONING AGENCY

**Temperature effects.** Changes of temperature tend to break up rocks. The heating of rock by day and its cooling by night produce some such change in it as is produced by the quick heating and cooling of glass. When the surface of the rock is heated, it expands, and a strain is set up between the hotter and more expanded part at the surface, and the cooler and less expanded part below.[1] This strain is enough to make the surface of the rock shell off in many cases. Daily variations in temperature are much more important than yearly variations, because they are much more common and take place more suddenly. Variations which do not involve the freezing of water are more important in long periods of time than those which do, because they are so very much more common. The daily range of temperature is influenced especially by (1) latitude, (2) altitude, and (3) humidity. (1) If other things were equal, the greatest daily ranges of temperature would be in low latitudes. (2) High altitudes favor great daily ranges of temperature, *so far as the rock surface is concerned*, for though the rock becomes heated during the sunny day, the thinness and dryness of the atmosphere allow the heat to radiate rapidly at night. Here, too, the daily range of temperature is likely to bring the wedge-work of ice into play. Since the south side of a mountain (in the northern hemisphere) is heated more than the north, it is subject to the greater daily range of temperature, and the rock on this side suffers the greater disruption. Similarly, rock surfaces on which the sun shines daily are subject to greater disruption than those

[1] It is the change of temperature *of the rock surface*, not the change of temperature of the air above it, which is considered here.

much shielded by clouds. (3) The daily range of temperature is also influenced by humidity, a rock surface becoming hotter by day and cooler by night beneath a dry atmosphere than beneath a moist one. Aridity, therefore, favors the disruption of rock by changing temperatures. The color of rock, its texture, and its composition also influence its range of daily temperature by influencing absorption and conduction. The disrupting effects of changes of temperature are slight or nil where solid rock is protected by soil, clay, sand, gravel, snow, or other incoherent material.

In view of these considerations, the breaking of rock by changes of temperature should be greatest on the bare slopes of isolated elevations of rock, where the atmosphere is dry. All these conditions are not often found in one place, but the disrupting

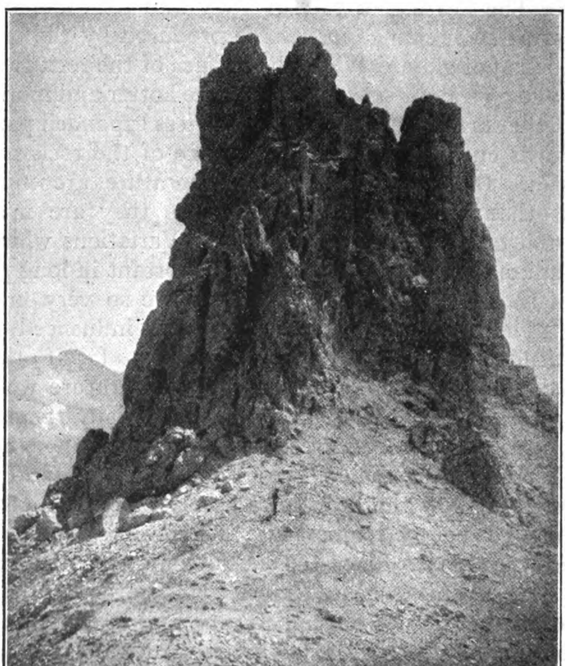


Fig. 17. A mountain top, illustrating a common condition of the rock in mountain peaks.

effects of changing temperatures are best seen where several of them are associated.

The importance of this method of rock-breaking is rarely appreciated except by those familiar with high and dry regions. Mountain climbers know that most high peaks are covered with broken rock to such an extent as to make their ascent dangerous to the uninitiated. High serrate peaks, especially of crystalline rock, are, as a rule, literally crumbling to pieces (Fig. 17). The piles of talus which lie on the slopes and at the bases of steep mountains are in some cases hundreds of feet in height, and their materials are in

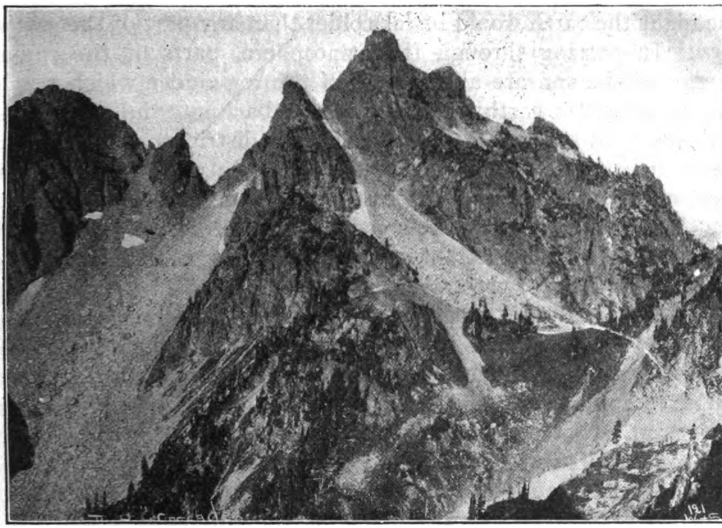


Fig. 18. Serrate mountain peaks with abundant talus. Cascade Mts., Wash.

large part the result of the process here under discussion. Masses of rock, scores and even hundreds of pounds in weight, are sometimes detached in this way, and started downward, and small pieces are much more common. The sharp peaks which mark the summits of most high mountain ranges (Fig. 18) are largely developed by the process here outlined. Even in low latitudes and moist climates the effects of temperature changes may be seen. For example, thin beds of limestone at the bottoms of quarries have been known to expand under the heat of the sun, so as to arch up and break.

The disruption of rock by changes of temperature is one phase of weathering. It tends to the formation of a mantle of rock waste, which, were it not removed, would soon completely cover the solid rock beneath and protect it from further disruption by heating and cooling; but the loose material thus produced becomes an easy prey to running water, so that the work of the atmosphere prepares the way for that of other eroding agencies.

**A thermal blanket.** The atmosphere is a thermal blanket to the rest of the earth. Without it the heat of the sun would reach the earth with far greater intensity than now, and it would be radiated back from the surface almost as rapidly as received. During the night the earth would be far colder than any part of the earth is now. In passing through the atmosphere, parts of the radiant energy of the sun are absorbed. Of the remainder which reaches the surface of the earth, a part is radiated back into the air by which it is absorbed and retained. The air thus distributes and equalizes the temperature. The constituents of the atmosphere which are most efficient in this work are water vapor and carbon dioxide, and the climate of the earth is believed to have been greatly affected by the varying amounts of these constituents, as well as by variation in the total mass of the atmosphere.

**Evaporation and precipitation.** Perhaps the most important work of the atmosphere as a geologic agent lies in its relation to the evaporation, circulation, and distribution of water. Atmospheric temperature is the primary factor governing evaporation, an important factor in the circulation of the vapor after it is formed, and controls its condensation and precipitation.

**Mechanical effects of rain.** In falling, the rain washes the atmosphere, taking from it much of the dust which the winds have lifted from the surface of the dry land. Not only this, but in passing through the atmosphere, the water dissolves some of its gases, so that when the rain reaches the land, the water is no longer pure. The dissolved gases enable it to dissolve various mineral matters on which pure water has little effect.

As it falls on the surface of the land, the rain produces various effects of a mechanical nature. (1) It leaves on the surface the solid matter taken from the air. (2) Clayey soils, baked under the influence of the sun, are softened by the rain, and more easily eroded by running water. (3) Under the influence of the expansion and contraction caused by wetting and drying, the soils and earths on

slopes creep slowly downward. (4) When rain falls on dry sand or dust the cohesion is at once increased, and shifting by the wind is temporarily stopped.

**Effects of electricity.** Another dynamic effect conditioned by the atmosphere is that produced by lightning. In the aggregate, this result is unimportant; yet instances are known where large bodies of rock have been fractured by a stroke of lightning, and masses many tons in weight have sometimes been moved appreciable distances. Incipient fusion in very limited spots is also known to have been induced by lightning. Thus where it strikes sand it may fuse the sand for a short distance, and, on cooling, the partially fused material is consolidated, forming a little tube or irregular rod (a *fulgurite*) of partially glassy matter. Fulgurites are usually but a few inches long, and more commonly than otherwise a fraction of an inch in diameter.

### SUMMARY

On the whole, the tendency of the work of the atmosphere, and of the work which is controlled by it, is to degrade the land, and to loosen materials of the surface so that they may be moved readily to lower levels by other agencies. The most important phase of the degradational work of the atmosphere is *weathering*, or the preparation of material for removal by other and more powerful agents of degradation. As we shall see, however, the atmosphere is not the only agent concerned in weathering.

The wind has doubtless been an important agent in the transportation of dust and sand, wherever and whenever there was dry land, ever since an atmosphere has existed. If it has been as effective as now through all the untold millions of years since there have been land and atmosphere, the total amount of work which it must have done is past calculation. Wind-deposited sand, now cemented into solid rock, has been identified, even in very ancient formations.

*Laboratory work.* The study of topographic and geologic maps, photographs, etc., illustrating wind work should be taken up in connection with this chapter. Plates XVI to XXII of Professional Paper 60 of the U. S. Geological Survey afford good illustrations of wind work. See also *Interpretation of Topographic Maps*, Exercise III, a laboratory manual (Henry Holt & Co.) which may be used with this text.

# CHAPTER III

## THE WORK OF GROUND (UNDERGROUND) WATER

The average amount of precipitation on the land is estimated at about 40 inches per year. A part of this water sinks beneath the surface, a part forms pools or lakes, a part runs off at once, and a part of it is evaporated. The proportion of the rainfall which follows each of these courses depends on several conditions, among which are (1) the topography of the surface, (2) the rate of rainfall (or the rate at which snow melts), (3) the porosity of the soil or rock, (4) the amount of water which the soil contains when the rain falls or the snow melts, (5) the amount of vegetation on the surface, and (6) the dryness of the atmosphere. The steeper the slopes, the more rapid the rainfall, the less porous the soil, the wetter it is, and the less the vegetation, the more water will run off without sinking beneath the surface.

The water which sinks into the ground becomes *ground-water.* The thousands of wells in lands peopled by civilized man, and the many springs which issue from the slopes of mountains and valleys prove that it is abundant and widely distributed.

That ground-water is connected intimately with rainfall is shown by the following facts: (1) The level of water in wells commonly sinks during droughts, and rises after rains; and the sinking is greater when the drought is long, and the rise greater when the rainfall is heavy. (2) Many springs discharge less water in times of drought, and others cease to flow altogether. (3) Rain-water is seen to sink beneath the surface, wherever the soil is porous. Sinking through the soil to the solid rock, it finds cracks and pores, and through them it descends to greater depths. Nowhere are the rocks which we see so compact and so free from cracks, when any considerable area is considered, as to prevent the sinking of water through them.

The amount of ground-water in a given region does not depend entirely on the local rainfall. Ground-water is constantly moving, and some of it flows far from the place where it entered. Thus

beneath the Great Plains of the West there is much water which fell on the eastern slopes of the Rocky Mountains. It has flowed beneath the surface to the plains, where some of it is drawn out for purposes of irrigation in regions where rainfall is deficient.

**Ground-water surface. Water-table.** If a well 60 feet deep fills with water up to a point 20 feet below the surface, it is because the material in which it is sunk is full of water up to that level. When the well is made, the water leaks into it, filling it up to the level to which the rock (or subsoil) is itself full. This level, below which the rock and subsoil (down to unknown depths) are full of water, is known as the *ground-water surface*, or *water-table*.

In a flat region of uniform structure and composition, the ground-water surface is essentially level, though it rises during wet weather, and sinks in times of drought. Its rise is due simply to the descent of rain water; but its sinking is due to several things: (1) Where there is growing vegetation, its roots draw up water from beneath; (2) evaporation goes on independently of vegetation; (3) the water is drawn out through wells, mines, etc., and runs out as springs; and (4) it flows underground from places where the water surface is higher to those where it is lower. In these and other minor ways the ground-water surface is depressed.

A well sunk to such a level as to be supplied with abundant water in a wet season may dry up during a period of drought, because the ground-water level is depressed below its bottom. Thus either well shown in Fig. 19 will have water during a wet season when the water-level is at *a*; but well 1 will go dry when the water surface sinks to *b*.

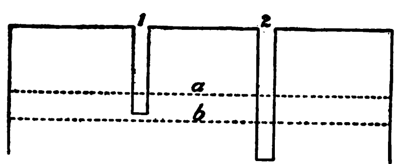



Fig. 19. Diagram illustrating the fluctuation of the ground-water surface; *a*=wet-weather ground-water level; *b*=ground-water level during drought.

Where the topography is not flat, the ground-water surface is not level. As a rule it is higher (though farther below the surface) under an elevation than under surrounding lowlands, as illustrated by Fig. 21. The reason is as follows: If a hill of sand is rained upon, most of the water falling on it sinks in. If the rain continues long enough the hill of sand will be filled with water, the water filling the spaces between the grains. The water in the hill tends to spread, but since the movement involves friction, the spreading

is slow. With the spreading, the surface of the water in the sand sinks, and sinks fastest at the center where it is highest. If no water were added, the surface of the water in the hill would, in


Fig. 20. Diagram showing how rain-water, falling in one place, may flow underground to another and there be brought to the surface. The layer *a* is porous, and water entering it in the mountains follows it to the plain.

time, sink nearly to the level of the water in the surrounding land; but at every stage preceding the last, the surface of the water would be higher beneath the summit of the hill than elsewhere, though

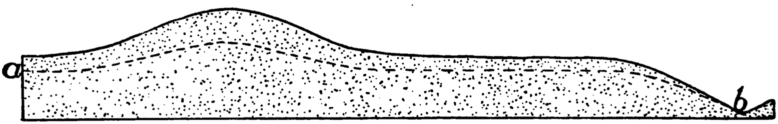



Fig. 21. Diagram illustrating the position of the ground-water surface (the dotted line) in a region of undulatory topography.

farther from the surface. In regions of even moderate precipitation the water-surface beneath the hills rarely sinks to the level of that in the lowlands about them, before it is raised by further rains.

The water-surface beneath lowlands also sinks. Some of the water finds its way into valleys, some of it sinks to greater depths, and some of it evaporates; but since the water-surface beneath the elevations sinks more rapidly than that beneath the lowlands, the two approach a common level. Their difference will be least at the end of a long drought, and greatest just after heavy rains.

**Depth to which ground-water sinks.** The depth to which ground-water sinks has not been determined by observation. The deepest excavations are but little more than a mile deep, and at this depth the limit of water is not reached. There is a popular belief that water sinks until it reaches a temperature sufficient to convert it into steam; but except in places where hot lava lies near the surface, this belief does not appear to be well founded. Its descent probably is stopped in quite another way.

Water descends through the pores and cracks of soil and rock,

and it doubtless goes down as far as they do. But it is probable that cracks do not go down more than a few miles, and that pores are limited to similar depths. The reason for this is that rock, solid and unyielding as it seems, is yet mobile under sufficiently great pressure. If cracks or openings were formed in it at great depths, it is calculated that they could not persist, for the rock, under the pressure which exists there, would "flow" in and close them. The flow is, in effect, much like the flow of a stiff liquid. The outer zone of the earth, where cracks and cavities may persist, is the *zone of fracture*, and it is probable that the descent of water under ordinary conditions, is limited to this zone, variously estimated to have a depth of six to eleven miles.[1]

**Movement of ground-water.**[2] Ground-water is in more or less continual movement. If all the water is pumped out of a well, it soon fills up again by inflow from the sides. Springs and flowing wells also demonstrate the movement of ground-water. Near the surface the movement is primarily downward if the rock through which it passes is equally permeable in all directions; but so soon as the descending water reaches the water-surface, its downward flow is checked, and its movement is partly lateral.

Ground-water moves chiefly by slow percolation, for most of it is not organized into definite streams. Small streams are seen in some caves, and subterranean streams issue as springs in some places; but most streams which issue as springs probably have definite channels for short distances only, before they appear at the surface. The "reservoirs" from which artesian wells draw their supply are porous beds of rock, containing abundant water. As the supply is drawn off at one point, it is renewed by water entering elsewhere. Since the freedom of movement of ground-water is influenced greatly by the porosity of the rock, and since the rock is, on the average, most porous near the surface, the movement of ground-water is greatest near the surface, and less and less with increasing depth. Movement in the lower part of the subterranean hydrosphere doubtless is extremely slow.

**Amount of ground-water.** The porosity of surface rocks varies

[1] Some recent experiments suggest that, at high temperatures and under great pressures, water may enter into combination with rock material, with contraction of volume. If so, water *in combination* (not free) may perhaps go below the zone of fracture. Barus. Bull. 92, U. S. Geol. Surv.

[2] For a full discussion of this subject see King, 19th Ann. Rept., U. S. Geol. Surv., Pt. II, and Slichter, Water Supply and Irrigation Paper 67, U. S. Geol. Surv.

widely, and the porosity of but few has been determined.[1] From such determinations as have been made, it is estimated that the average porosity of the outer part of the lithosphere is somewhere between five and ten percent. If the porosity diminishes at a constant rate to a depth of six miles (where it becomes zero), the average porosity to this depth would be half the surface porosity. An average porosity of 2½% would mean that the rock might contain enough water to form a layer nearly 800 feet deep, if brought out to the surface.[2]

It is probable that the porosity decreases in more than an arithmetic ratio, both because the deeper rocks are not so generally of porous kinds as those at the surface, and because of the pressure which tends to close openings. For this reason it may be that the figure given above is too large, even for the land. The porosity beneath the sea is probably less than that beneath the land, so that for the earth, 800 feet is perhaps too high a figure, and is not to be regarded as a measurement.

**Fate of ground-water.** Most of the water which sinks into the earth reaches the surface again after a longer or shorter journey. Some of it is evaporated from the surface directly, some is taken up by plants and passed by them into the atmosphere, some issues in the form of springs, some seeps out, some is drawn out through wells, and much of the remainder finds its way underground to the sea or to lakes, seeping out beneath them. A small portion of the descending water enters into combination with mineral matter. It does not necessarily follow, however, that the total supply of water is for this reason decreasing. Minerals once hydrated may be dehydrated, the water being set free. Furthermore, considerable quantities of water in the form of vapor issue from volcanoes, and some volcanic vents continue to steam long after volcanic action proper has ceased. It is probable that some, and perhaps much of the water issuing from these vents has never been at the surface before. The amount of water reaching the surface of the earth for the first time from volcanoes, may, so far as now known,

[1] Buckley, Building and Ornamental Stones, Bull. IV, Wis. Surv.; Merrill, Stones for Building and Decoration.

[2] Slichter estimates that the ground-water is sufficient in amount to cover the earth's surface to a depth of 3,000 to 3,500 feet: Water Supply and Irrigation Paper No. 67, U. S. Geol. Surv. Earlier estimates gave still higher figures. Fuller, in a recent estimate, places the amount at about 100 feet: Water Supply and Irrigation Paper 160, U. S. Geol. Surv.

equal or even exceed the amount consumed in the hydration of minerals.

### WORK OF GROUND-WATER

Ground-water works chemically and mechanically, the chemical work being the more important.

**Chemical work.** The chemical and chemico-physical action of ground-water may be grouped in several more or less distinct categories.

1. The simplest result is the *solution* of mineral matter. Pure water dissolves little mineral matter; but the carbon dioxide extracted from the atmosphere, and the products of organic decay extracted from the soil, give the water added power to dissolve. The solvent work of ground-water is shown by the fact that all water from springs and wells contains mineral matter, while rain water is essentially free from it. The subtraction of soluble matter from rock tends to make it porous, and helps it to decay.

Fig. 22. Sections of petrified logs, near Holbrook, Ariz. Age probably Jurassic.

2. One mineral substance in solution may be substituted for

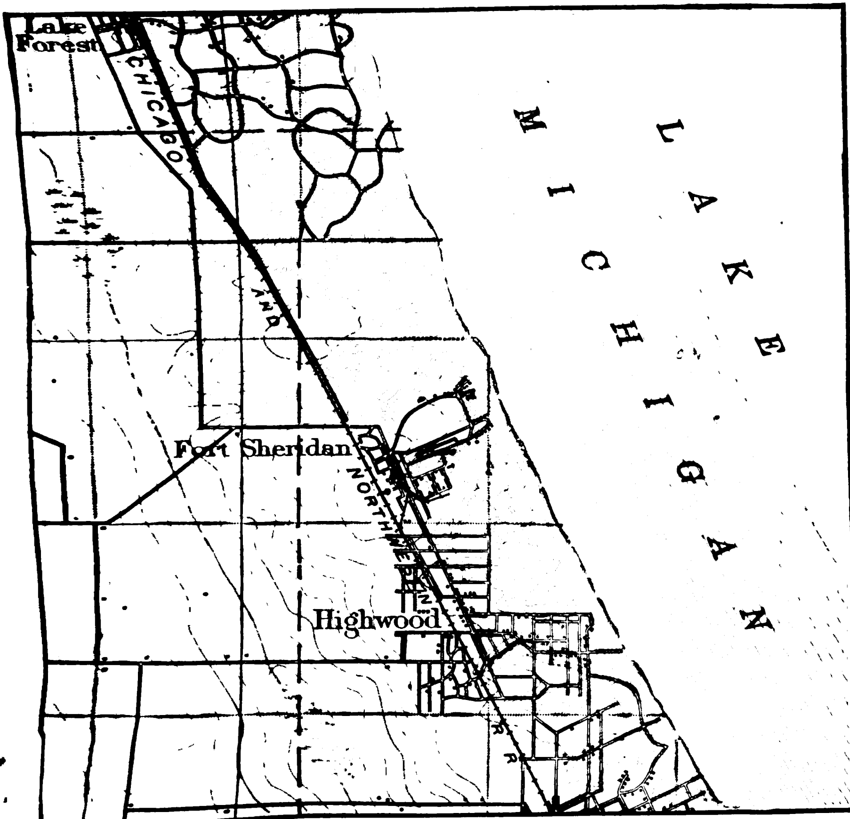
another extracted from the rock. Thus the lime carbonate of a shell imbedded in rock may be removed, molecule by molecule, and some other substance, such as silica, left in its place. When the process is complete, the substance of the shell has been completely removed, though its form and structure are preserved in the new material. Buried logs may be converted into stone by the substitution of mineral matter for the vegetable tissue (Fig. 22).

3. Materials dissolved from rock at one point may be deposited in other rock elsewhere. Thus a third type of change, *addition*, is effected. Rock may at one time and place be rendered porous by the subtraction of some of its substance, and the openings thus formed may later become the receptacles of deposits from solution. This is exemplified in the stalactitic deposits of many caves. Not uncommonly cracks and fissures are filled with mineral matter deposited by the waters which pass through them, making *veins*.

4. A further series of changes is effected by ground-water when the mineral matter it contains enters into combination with the mineral matter through which it passes. In the long course of time, changes of this sort may be so great as to change rock completely.

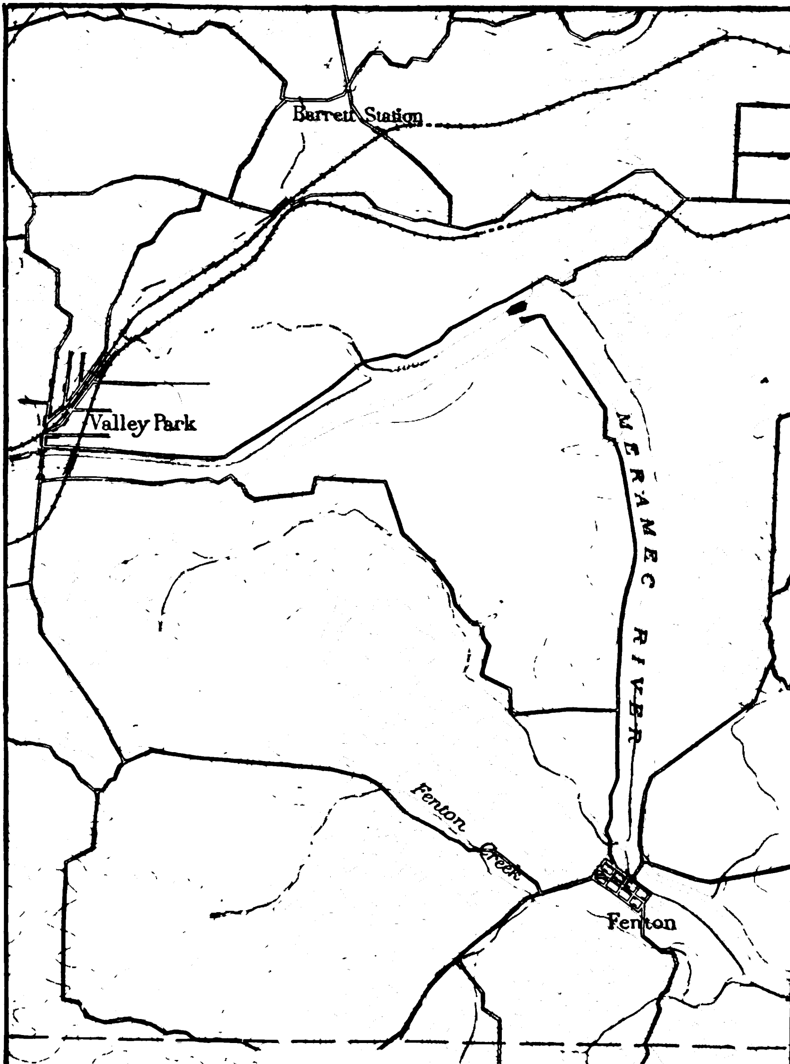
*Importance of solution.* Calculations have been made which illustrate in a measure the quantitative importance of solution by ground-water. Most of the mineral matter dissolved in streams was contributed by ground-water (springs, etc.) flowing to them, and the amount in stream water is determined readily. The Thames River drains an area only about one-tenth as large as the State of New York, but it is estimated to carry about 1,500 tons of mineral matter in solution to the sea daily. From the uppermost 20,000 square miles of its drainage basin, the Elbe is estimated to carry yearly about 1,370,000 tons of mineral matter in solution. Such figures make it clear that ground-water is an effective agent in the lowering of land surfaces. It is estimated that something like one-third as much matter is carried to the sea in solution as in sediment.

The importance of the solution effected by ground-water is shown in another way. It is probable that most of the salt of the sea has been taken to it in solution by waters flowing from the land. The amount of salt is stupendous (Chapter VI). Furthermore, most of the limestone of the earth has been extracted from sea-




*Youthful valleys.* Shore of Lake Michigan just north of Chicago. Scale, about 1 mile per inch. Contour interval, 10 feet. (Highwood, Ill., Sheet, U. S. Geol. Surv.)

PLATE IV




A stream widening its valley by lateral planation. Scale, about 1 mile per inch. Contour interval, 20 feet. (Missouri, U. S. Geol. Surv.)

water, whither the larger part of it was carried by streams, and the aggregate amount of limestone is far greater than the amount of salt in the sea. Some other sorts of rock, such as gypsum, of less importance quantitatively, have had a similar history.

In general, solution is probably most effective at a relatively slight distance below the surface. In the mantle rock, the materials are as a rule less soluble than below, for in many places they represent the residuum after the soluble parts of the formation from which they originated were dissolved out. Below this zone, the rock contains more soluble matter, and the water, charged with organic matter in its descent through the soil, is in condition to dissolve it. At still greater depths the water has become saturated to some extent, and, so far forth, less active. At great depths, too, the movement is less free. Increased pressure on the other hand facilitates solution at great depths.

*Deposition of mineral matter from solution.* Mineral matter is deposited from solution under various conditions. (1) Some of it is deposited by *evaporation.* This is shown where water seeps out on arid lands. (2) *Reduction of temperature* may occasion deposition. In general, hot water is a better solvent of mineral matter than cold,[1] and if hot water issues with abundant mineral matter in solution, some of it is likely to be precipitated on cooling. (3) Certain *plants* cause the precipitation of mineral matter from solution, as about some hot springs in which algæ grow in profusion. These little plants are a chief factor in the deposits about the hot springs of Yellowstone Park.[2] (4) A fourth factor involved in the deposition of mineral matter is *relief of pressure.* Pressure increases the solvent power of water directly; it also increases the amount of gas which may be dissolved, and this in turn increases the solvent power of the water for some minerals. As water charged with gas comes to the surface, pressure is lessened, and some of the gas escapes. In numerous cases, mineral matter is then precipitated. (5) Precipitation is sometimes effected by the mingling of waters containing different mineral substances in solution. Such mingling of solutions is most common along lines of ready subterranean flow,

[1] This is not true in the case of minerals, such as the carbonates, dissolved and held in solution under the influence of gases dissolved in the water.

[2] Weed. The Formation of Hot Springs Deposits; Excursion to the Rocky Mountains, and Ninth Ann. Rept. U. S. Geol. Surv., pp. 613–76; and B. M. Davis, Science, Vol. VI, pp. 145–57, 1897.

and while each portion of the water entering a crevice or porous bed might have been able to keep its own mineral matter in solution, their mingling may involve chemical changes resulting in the formation of insoluble compounds, and therefore in deposition. This principle probably has been involved in the making of many veins of ore.

The deposition of material held in solution is most notable at two zones, one below that of most active solution, and the other at the surface, where evaporation is greatest. Under proper conditions, however, deposition may take place at any level reached by water.

**Mechanical work.** The mechanical work of ground-water is relatively unimportant. Where it flows in definite streams, the channels through which it flows are likely to be increased by mechanical erosion as well as by solution. Either beneath the surface or after the streams issue, the mechanical sediment carried will be deposited.

## RESULTS OF THE WORK OF GROUND-WATER

**Weathering.** Where the solvent work of ground-water is slight and equally distributed, its effect is to make the rock porous. If, for example, some of the cement of sandstone is dissolved, the rock becomes more porous; but if all the cement is removed, the

Fig. 23. Diagram to illustrate the form and relations of caverns developed by solution. The black spaces represent caverns. Small limestone sinks are represented at the surface where the roofs of caves have fallen in.

rock is changed to sand. If a complex crystalline rock contains among its minerals some one which is more soluble than the others, that one may be dissolved. This has the effect of breaking up the

rock, since each mineral acts as a binder for the rest. It may happen that no one of the minerals is dissolved completely, but that one or more of its constitutents is removed. Such change may cause the mineral to crumble, and so destroy the integrity of the rock. These are phases of weathering.

**Caverns.**[1] In formations like limestone, which are relatively soluble, considerable quantities of material may be dissolved from a given place. Instead of making the rock porous, in the usual sense of the term, caverns are developed (Fig. 23). In their production, solution may be abetted by the mechanical action of the water passing through the openings which solution has developed.

Caves are numerous in central Kentucky and southern Indiana, and the size of some of them, such as Mammoth and Wyandotte, is very great. A ground-plan of Wyandotte (Ind.) Cave is shown in Fig. 24. The aggregate length of its passageways is a number of miles.

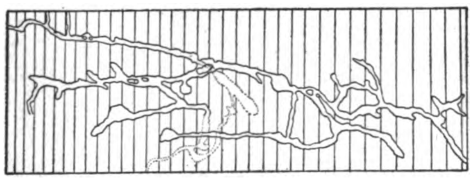


Fig. 24. Ground-plan of Wyandotte Cave. The unshaded areas represent the passageways. (21st Ann. Rept., Ind. Geol. Surv.)

Deposition may take place in caves after they are formed (Fig. 25), or it may even go on at the same time that the cave is being excavated. Stalactites and stalagmites are common forms of cave deposits. A stalactite may start from a drop of water leaking through the roof of the cave. Evaporation, or the escape of gases in solution, results in the deposition of some of the lime carbonate about the margin of the drop, in the form of a ring. Successive drops make successive deposits on the lower edge of the ring, which grows downward into a hollow tube through which descending water passes, making its chief deposits at the end. Deposition in the tube ultimately may close it, while deposition on the outside, due to the water trickling down in that position enlarges it.

**Limestone sinks.** Underground caves give rise to topographic features of local importance. If the roof of a cavern collapses, it causes a sink or depression in the surface. Some regions of limestone caves are affected by numerous sinks formed in this way.

[1] For a racy account of caverns see Shaler's *Aspects of the Earth.*

These *limestone sinks* (Figs. 26 and 23) as they are called, are conspicuous in the cave region of Kentucky, and are well known in many other limestone districts. Some limestone sinks are made in other ways.

**Creep, slumps, and landslides.** When the soil and subsoil on a slope become charged with water, they tend to move downward. When the movement is too slow to be sensible it is called *creep;* when rapid enough to be sensible, the material is said to *slump* or *slide.* This may happen when the slope on which water-charged mantle-rock lies is steep (Fig. 27). Some landslides have done great damage. Where a stream's bank are high, and of unindurated material, such as clay, considerable masses sometimes slump from the bank into the river, or settle away slowly from their former positions. The same thing takes place on a larger scale on the slopes of steep mountains.[1] In creep and in landslides gravity is the force involved, and the ground-water only a condition which makes gravity effective.

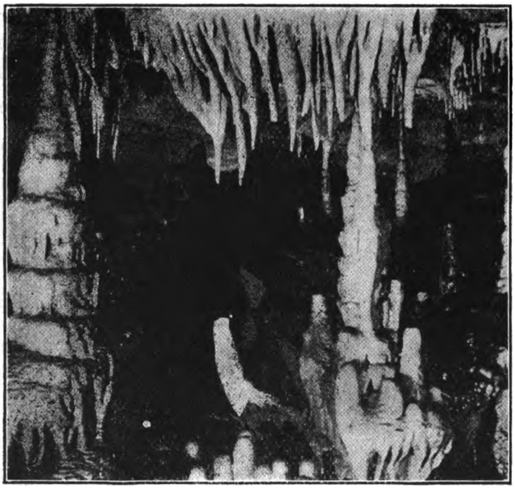


Fig. 25. Stalactites and stalagmites in Marengo Cave, southern Indiana. (Hains.)

ORE-DEPOSITS

Many ore-deposits are but a special result of the chemical work of ground-water, and are of interest because of their industrial value. An *ore* is a rock that contains a metal that can be extracted profitably, though the term is often extended to include unwork-

[1] Russell has emphasized this point in 20th Ann. U. S. Geol. Surv., Pt. II, pp. 193–202, and Cross, 21st Ann. U. S. Geol. Surv., Pt. II, pp. 129–150.

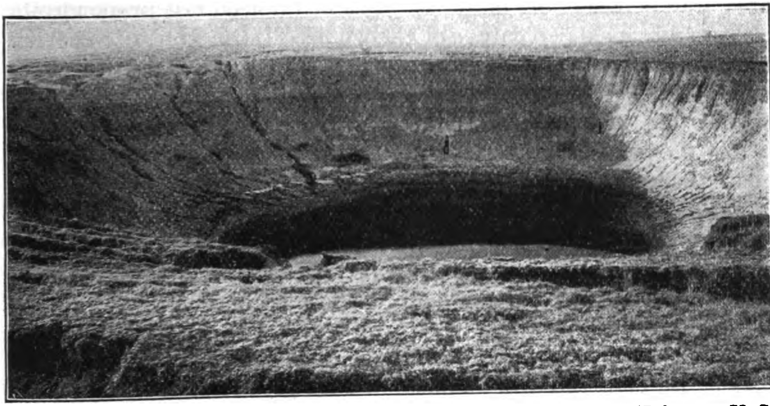


Fig. 26. A sinkhole of recent development near Meade, Kan. (Johnson, U. S. Geol. Surv.)

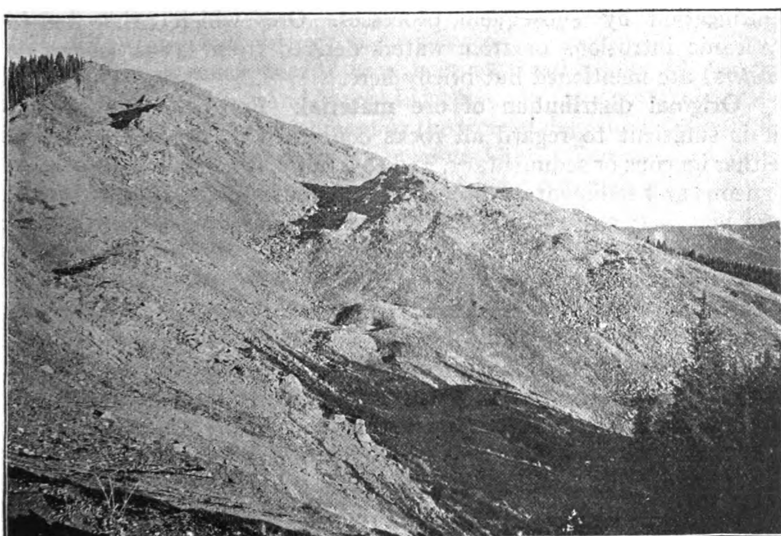


Fig. 27. South face of Landslip Mountain, Colo. The protruding mass on the right has slumped down. (U. S. Geol. Surv.)

able, lean bodies of ore material. The metal need not preponderate, or form any fixed percentage of the whole. Little gold ore contains more than a very small fraction of one per cent of the precious metal, while high-grade iron ore yields sixty-odd per cent of the metal. In iron ore, the metallic oxide or carbonate makes up nearly the whole rock; in gold ore, the metal is one of the least abundant constituents.

Metals are disseminated widely through the rock substance of the earth, and even through the hydrosphere; but in their disseminated condition they are not ores. The concentration of the metals into workable richness, in accessible places, is the essential thing in the formation of ores. The degree of concentration required is measured by the value of the metal. The chief points about ores to be considered in connection with ground-water are (1) the original distribution of the metallic materials, (2) their solution by circulating waters (or, rarely, by other means), (3) their transportation in solution to the place of deposit, (4) their precipitation in concentrated form, and (5) perhaps their further concentration and purification by subsequent processes. Ores which originated in volcanic intrusions or from waters derived from lavas (*magmatic waters*) are mentioned but briefly here.

**Original distribution of ore material.** For present purposes it is sufficient to regard all rocks concerned in ore-deposition as either igneous or sedimentary, and to inquire, first, how far ordinary igneous and sedimentary processes contribute to the segregation of ore material; and second, what the subsequent processes of local concentration are.

**Magmatic segregation.** The segregation of metals in lava is known as *magmatic segregation*. In some instances masses of iron ore seem to have originated in this way. It is not improbable that the segregation of metallic iron and nickel, and perhaps other metals, may be common in the deeper parts of the earth, but it is not clear that many known ores originated in this way. It is probable, however, that there may be some segregation of metallic substances in lavas. While this segregation may not be rich enough to make ore, it may determine the places where subsequent concentration takes place, by the help of ground-water.

**Marine segregation and dispersion.** In the formation of the sedimentary rocks there was notable metallic enrichment in some places. The ground-waters of the land, after their subterranean

circuits, carried to the seas various metallic substances in solution. In the main these substances appear to have been widely diffused, and to have been distributed very sparsely through the sediments, for sediments seem to contain less ore material than igneous rocks. There are however important exceptions to this general rule of sedimentary leanness.

The iron-ore beds of Clinton age ranging from New York to Alabama, and appearing also in Wisconsin and Nova Scotia, form a stratum in the midst of ordinary sediments, and contain marine fossils. The great iron-ore beds of Lake Superior also were sedimentary in origin, and so, probably, were most other important iron deposits. Not all sedimentary iron-ore deposits are of marine origin, and most of them are not clastic. Many of the sedimentary iron ores have been changed greatly from the condition in which the ferruginous matter was first deposited. In this change, ground-water has been the chief agent. Beds of clastic iron ore are known in Europe. The ore matter was in older rocks, and was segregated, mechanically, during sedimentation, because it was much heavier than other contemporaneous sediments. Its superior weight had much the same effect as greater coarseness.

Some limestones appear to have been enriched locally, in a lean way, in lead and zinc, and rarely in copper, in the course of their formation. This lean enrichment at the time of deposition probably determined the development of ore regions later. The lead and zinc ore regions of the Mississippi basin have been regarded as areas of this sort, the subsequent concentration of the metal into ores being the work of ground-water. The lean enrichment accompanying sedimentation has been attributed to solutions of the metals brought to the sea from neighboring lands, the metals being then precipitated by organic action in the sea-water.[1] This organic action may have been more effective in some areas than in others, because of the unequal distribution of life and the concentration of its decaying products.

Since it is reasonable to suppose that land-waters, on reaching the margins of the water-basins, must here and there find conditions favorable for the precipitation of their metallic contents, it is inferred that while the processes of sedimentation tended on the whole to leanness, they gave rise to (1) some very important ore-deposits, notably many iron ores, the greatest of all ores in

[1] Chamberlin. Geol. of Wis., Vol. IV, p. 599, et seq., 1882.

quantity and in industrial value, and (2) a lean enrichment of the sediments of certain other areas which, after subsequent processes of concentration of the metals by ground-water, became productive.

**Origin of ore regions.** From these considerations it appears that the fundamental explanation of many "mining regions" is to be found in (1) magmatic segregation, so far as the country rock is igneous, and (2) enrichment during sedimentation, so far as the rock is secondary. Either of these processes may, in rare cases, give rise to ores directly; but in most cases, further concentration of the metallic substances is necessary. This concentration is effected in various ways by the help of ground-water.

1. **Surface concentration.** The simplest of all modes of concentration takes place in the formation of mantle-rock. An insoluble or slightly soluble metallic substance sparsely distributed through rock may be concentrated to working value by the decay and removal of the principal rock material, leaving the metallic matter in the residuary mantle. The tin ores of the Malay peninsula [1] are examples. Crystals of tin oxide were originally scattered sparsely through granite and limestone. By the decay and partial removal of the rock, the crystals have accumulated in workable quantities. Certain gold fields and certain iron ores have acquired higher value in the same way; also certain ores of manganese, as those of Arkansas. Such *residuary ores* may be further concentrated by running water, because the greater weight of the metals causes them to be left behind when the lighter substances are washed away, or because their greater weight causes them to be partially separated from the other sediments, in deposition. Gold placers are the best example.

2. **Purification.** A different mode of concentration and purification has affected some of the great iron deposits. As already stated, the iron compounds were originally parts of a sedimentary formation, and in beds. In some cases they were sufficiently pure, as first deposited, to be worked profitably; but in most cases they were affected by impurities. From such deposits the impurities have been dissolved by the percolation of waters, and at the same time, more of the valuable metal has been added. The great Bessemer iron-ore deposits of Lake Superior are examples. Originally impure silicates or carbonates, they have been converted into rich and

[1] Penrose. Jour. of Geol., Vol. XI, pp. 135–155, 1903.

phenomenally pure ferric oxides by ground-water. There are vast quantities of lean ores in the same region not thus purified and enriched.[1]

**3. Solution and re-precipitation.** Ore material may be leached out of the surface-rock by water circulating slowly through it, and carried on until it reaches some substance which causes a reaction that precipitates the metallic matter. This substance may be a constituent of some rock which the circulating water encounters; but more commonly, the precipitation seems to be due to the mingling of waters charged with different mineral substances, the mingling inducing reactions which result in the precipitation of the ore. Precipitation does not necessarily follow such commingling; it takes place only when the mingling waters reduce the solubility of the ore material sufficiently. Changes of pressure and temperature also may enter into the process.

Otherwise stated, the general process of underground ore formation appears to be this: The permeating waters dissolve the ore material disseminated through the rock, and carry it thence into the main channels of circulation, usually the fissures, porous parts, or cavernous spaces. If precipitating conditions are found there, deposition takes place. The precipitating conditions may be merely changes of physical state, such as cooling or relief of pressure; but probably much more generally they are found in the commingling and mutual reaction of waters that have pursued different courses, and are differently mineralized.

**Location of greatest solution.** Water circulation is probably very slight below the depth of a mile or two, and above that depth there is little reason for supposing that the rocks of one horizon are more metalliferous than others of their kind. Thus there is no assignable reason why the igneous or sedimentary rocks at the surface are not as rich in ore material as the igneous rocks two or three miles below. For a given amount of water, solvent action is probably greatest where the temperature and pressure are highest, that is, in the deeper reaches of water circulation; but the *amount* of water passing in and out of the deeper zone is small compared with that of higher levels, and the total solvent action is quite certainly much greater in the upper zone than in the lower. At the same time, the solutions in the upper zone are quite certainly more dilute than those below. The horizon of greatest solution doubtless lies be-

[1] Van Hise & Leith, various monographs of the U. S. Geol. Surv.

tween the surface and a level slightly below the ground-water surface (p. 31); in other words, in the zone where atmosphere and hydrosphere co-operate. Surface-waters are charged with atmospheric and organic acids and other solvents, and their general effect upon the rocks is markedly solvent down to and somewhat below the permanent water-level. Concentration by residual accumulation may take place in this zone, as already noted, if the metallic compounds resist solution; otherwise this zone is depleted of its ore material by solution, and preparation is made for deposition elsewhere.

Solution also continues to take place varyingly as the water descends below this zone of dominant solution, and extends probably to the full depth of water circulation; but in the deeper circuit, precipitation also takes place, and with the waters taking up and throwing down material at the same time, it is difficult to estimate the balance of results. It is probable, however, that the result of these processes is to promote the development of the higher ore values at levels near enough the surface to be accessible, and along the main lines of ground-water circulation.

**Influence of contacts.** As many ore-deposits depend on a dissolving state of the waters followed by a depositing state, it is obvious that conditions which favor changes of state and the commingling of different kinds of water, are apt to be favorable to ore production. At any rate it is observed that many important ore-deposits occur at the contact of unlike formations, as for example at the contact of igneous rock with limestone. It is not to be inferred that such contacts are generally accompanied by workable ore-deposits, but merely that a notable proportion of workable ore-deposits occur at such junctions. It is rational to suppose that where the chemical nature of the two formations is in contrast, the waters that percolate through the one are likely to be mineralized very differently from those that course through the other, and that on mingling at the contact, reactions are liable to take place. When a valuable metallic substance is present, it may be involved and, by chance, suffer precipitation. Reactions are the more probable because the contact plane of formations is, in some cases, a plane of crustal movement, and hence more or less open and accompanied by fractures, zones of crushed rock, and other conditions that facilitate circulation and offer suitable places for ore formation.

**The effect of igneous intrusions.** A special case of much im-

portance arises where lavas are intruded into sediments that have previously been partially enriched in the ways described above. The igneous intrusion not only introduces new contact zones, and more or less fracturing, but it brings into play hot waters with their intensified solvent work, their more active circulation, and the reaction between waters of different temperatures. The special efficiency of these agencies is believed to be important in many cases. Furthermore the intruded lava may be rich in metallic substances, and so be a favorable site for later concentration. The magmatic waters themselves appear to be a source of important ore-deposits, as already noted, and the present tendency is to attach more and more importance to them. Ores deposited by magmatic waters are, in a sense, the product of magmatic segregation (p. 42).

**The influence of rock walls.** The rock walls themselves are thought to be a factor, in some cases, in the reactions which precipitate ores. It appears that the effect of the wall may be to withdraw some constituent of the passing solution, and destroy its equilibrium in such a way as to cause the precipitation of metallic constituents. Once deposited on the walls, ore aids the further accretion of matter of the same sort. The effect of the rock wall here noted is sometimes called *mass action.*

The special forms assumed by ores deposited from solution underground (veins, beds, etc.), are incidental to the local situation in which the precipitation takes place.

### SUMMARY

All in all, *ground-water* is to be looked upon as a most important geological agent. When it is remembered that a very large part of all the water which falls on the surface of the earth, either in the form of rain or snow, sinks beneath the surface; that some of it sinks to a great depth; that much of it has a long underground course before it reappears at the surface; that it is everywhere and always active, either in *subtracting* from the rock through which it passes, in *adding* to it, in effecting the *substitution* of one mineral substance for another, or in bringing about *new chemical combinations;* and when it is remembered that these processes have been going on for untold millions of years, it will be seen that the total result accomplished must be great. The rock formations of the earth to the depths to which ground-water penetrates, are to

be looked upon as a sort of chemical laboratory through which waters are circulating in all directions, charged with many sorts of mineral substances. Some of the substances in solution are deposited beneath the surface, and some are brought to the surface where the waters issue. Much of the material brought to the surface in solution is carried to the sea and utilized by marine organisms in the making of shells. Without the mineral matter brought to the sea by springs and river, many shell-bearing animals of great importance, geologically, would perish. Biologically, therefore, as well as geologically, ground-water is of great importance. It is also of prime importance in the development of ores.

### SPRINGS AND ARTESIAN WELLS

**Springs.** The term *spring* is applied to any water which issues from beneath the surface with volume enough to form a distinct current. If water issues so slowly as merely to keep the surface moist, it is *seepage* but not a spring.

Many springs issue from the sides of valleys (Fig. 28), the bottoms of which are below ground-water level. They are especially likely to issue at the surface of relatively impervious layers, and where the valley slopes cut joints, porous beds, or other structures which allow free flow of ground-water.

Springs are classified in various ways, and the several classifications suggest characteristics worthy of note. They are sometimes classed as *deep* and *shallow*, but the idea involved in this

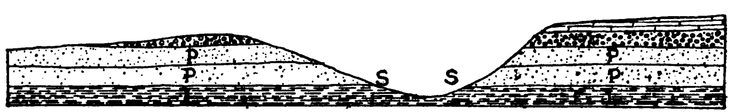



Fig. 28. Diagram showing conditions favorable for springs, in the side of a valley. P, porous rock, and I, impervious. Rain-water sinks to I, and, moving along its surface, comes out as springs at S and S.

grouping would be better expressed by *strong* and *feeble*. They are also classed as *cold* and *thermal*, the latter term meaning that the temperature is such as to make the springs seem warm or hot. The temperature of thermal springs ranges up to the boiling-point of water. Again, some springs are *continuous* in their flow, while others are *intermittent*. Most intermittent springs flow after periods of rain, but dry up during droughts. Springs are also classified as

*mineral* and *common*. Mineral springs, in the popular sense of the term, are of two types: (1) Those which contain an unusual amount of mineral matter, and (2) those which contain some unusual mineral. All springs which are not mineral are common. This classification is not very significant, for all springs contain more or less mineral matter, and many springs which are "common" contain more mineral matter than some which are "mineral." Mineral springs are themselves classified according to the kind and amount of mineral matter they contain. Thus *saline* springs contain salt; *sulphur* springs contain compounds (especially gaseous) of sulphur; *calcareous* springs contain abundant lime carbonate, etc. *Medicinal* springs are those which contain some substance which has, or is supposed to have, curative properties.

**Geysers.** Geysers are intermittently eruptive hot springs. They occur only in volcanic regions (past or present), and in but few of them, being known only in the Yellowstone National Park, Iceland, and New Zealand.

The cause of the eruption is steam. The surface-water sinks down until, at some unknown depth, it comes in contact with rock sufficiently hot to boil it. The source of the heat is not open to inspection, but it is believed to be the uncooled part of extruded or intruded lava. From what was said earlier in this chapter it is clear that geysers do not have their origin in water which sinks down to the zone of great heat, where the downward increment of heat is normal.

The water of a geyser issues through a tube of unknown length. Whether the tube is open down to the source of the heat is not determinable, but water from such a source finds its way to the tube. Water may enter the tube from all sides and at various levels. The heating may precede or follow its entrance into the tube, or both. So far as the water is heated after it enters the tube, the point of most rapid heating may be at the bottom of the tube, or at some point above. If the water were converted into steam as fast as it enters the tube, steam would escape continuously, and there would be no geyser; but if the rock is only hot enough to bring the water in the tube to the boiling-point after some lapse of time, and after a good deal of water has accumulated, an eruption is possible.

The exact sequence of events which leads to an eruption is not known, but a definite conception of the principles involved may

be secured by a definite case. Suppose a geyser-tube full of water and heated at its lower end. As the water is heated below, convection tends to distribute the heat throughout the column of water above. If convection were free and the tube short, the result would be a boiling spring; but if the tube is long, and especially if

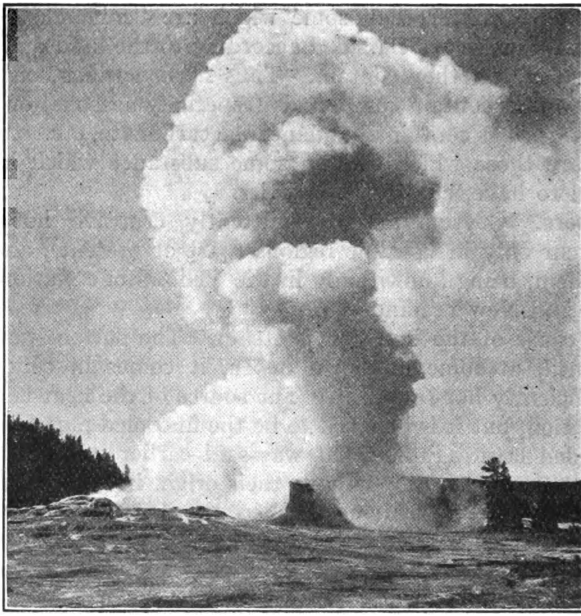


Fig. 29. Giant Geyser, Yellowstone National Park. (Wineman.)

convection is impeded, the water at some level below the surface may be brought to the boiling-point earlier than at the top. If even a little water in the lower part of the tube is converted into steam, the steam will raise the column of water above, and it will overflow. The overflow relieves the pressure on all parts of the column of water below the surface. If before the overflow there was any considerable volume of water essentially ready to boil, the relief of pressure following the overflow might allow it to be converted into steam suddenly, and the sudden conversion of a considerable quantity of water into steam would cause the eruption of all the water above it (Fig. 29). The height to which the water

would be thrown depends upon the amount of steam, the size and straightness of the tube, etc.

It is clear that everything which impedes convection in the geyser tube will hasten the period of eruption, since impeded circulation will have the effect of holding the hot water down, and so of bringing the water at some level below the top more quickly to boiling. It follows that anything which chokes the tube, or which increases the viscosity of the water, hastens an eruption.[1]

Fig. 30. The cone of Lone Star Geyser, Yellowstone National Park. (U. S. Geol. Surv.)

Some geysers build up crater-like basins or cones (Figs. 30 to 32) about themselves, the cone being of material deposited from solution (p. 37). The brilliant colors of some of the deposits about the springs in the Yellowstone Park are attributed to the little plants which cause the deposition. When the water from any geyser or hot spring ceases to flow, the plants die and the colors disappear.

The heating of geyser water must cool the lava or other source of heat below. As this takes place, the time between eruptions becomes longer and longer. In the course of time, therefore, the geyser must cease to be eruptive, and when this change is brought about, the geyser becomes a hot spring. Within historic time several geysers in the Yellowstone Park have ceased to erupt and new ones have been developed. There are something like 3,000 vents of all sorts in this park, hot springs which are not eruptive greatly outnumbering geysers.

A few geysers have somewhat definite periods of eruption. Of such "Old Faithful" is the type; but even this geyser, which formerly erupted at regular intervals of about an hour, is losing the reputation on which its name was based. Not only is its period of eruption lengthening, but it is becoming irregular, and the

[1] Weed. Am. Jour. Sci., Vol. XXXVII, 1889, pp. 351–59.

irregularity appears to be increasing. In the short time during which this geyser has been under observation its period has changed from a regular one of 60 minutes, or a little less, to an irregular one of 60 to 90 minutes. In the case of some geysers, years elapse between eruptions, and in some the date of the last eruption is so remote that it is uncertain whether the vent should be looked upon as a geyser or merely a hot spring.

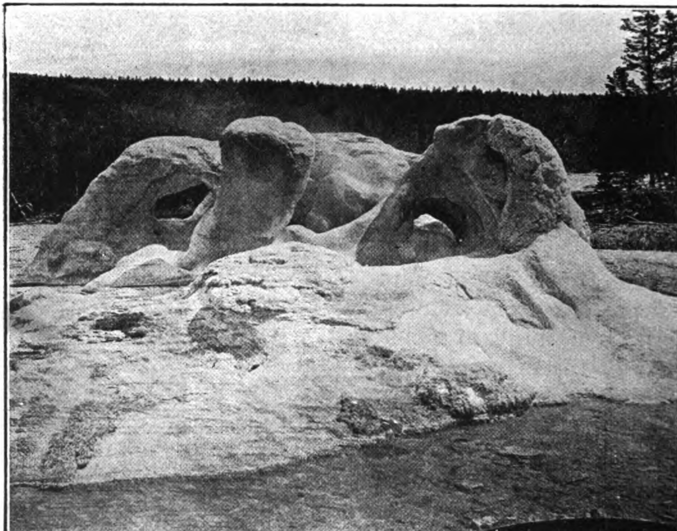


Fig. 31. Cone (or crater) of Grotto Geyser, Yellowstone Park. (Detroit Photo. Co.)

**Artesian wells.** The terms *artesian* well and *flowing* well were synonymous originally; but any notably deep well is now called *artesian*. The artesian well which does not flow does not differ from a common well in principle, while the flowing well is really a gushing spring, the opening of which was made by man.

Flowing wells [1] depend upon certain relations of rock structure, water supply, and elevation. Generally speaking, a flowing well is possible in any place underlain by any considerable bed of porous

[1] Chamberlin. Geol. of Wis., Vol. I, pp. 689–97, and Fifth Ann. Rept., U. S. Geol. Surv., pp. 131–73. The former a brief, and the latter an elaborate, exposition of the principles involved.

rock, if this rock outcrops at a sufficiently higher level in a region of adequate rainfall, and is covered by a layer or bed of relatively impervious rock. This statement involves four conditions, all of which are illustrated by Fig. 34, where *a* is the bed of porous rock. It is not necessary that the beds of rock form a basin, nor is it neces-

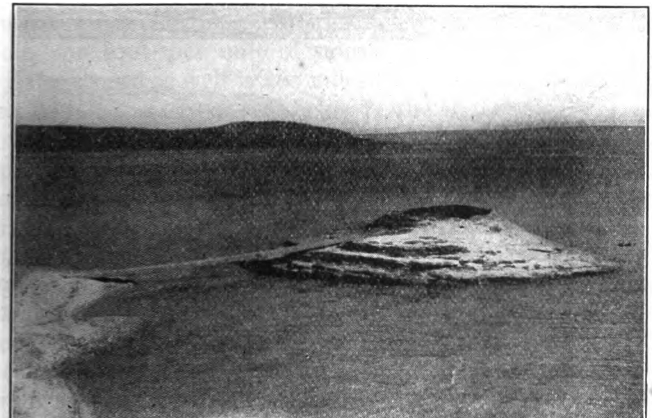


Fig. 32. Deposit from a hot spring in Yellowstone Lake. (Fairbanks.)

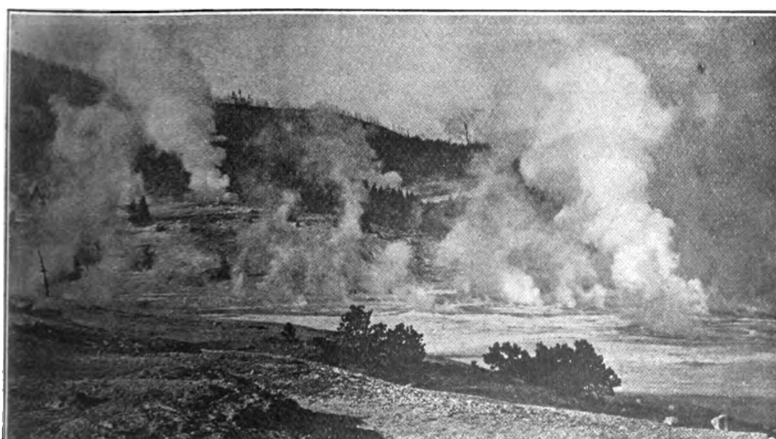


Fig. 33. Hot springs and geysers. Norris Geyser Basin, Yellowstone Park.

sary, commonly, to take account of the character of the rock beneath the porous bed which contains the water.

The bed of porous rock is the "reservoir" of the flowing well. Sand or sandstone, and gravel or conglomerate, most commonly

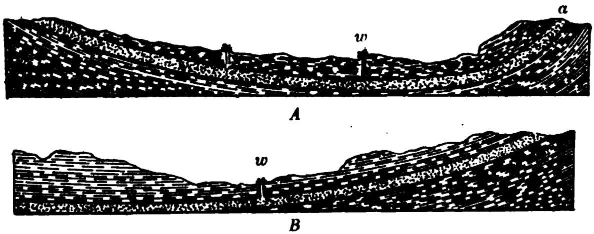



Fig. 34. Diagrams illustrating conditions favorable for artesian wells. In *A*. the porous bed *a* is in the form of a basin; in *B*, it merely dips.

serve as the reservoirs. In order that they may contain abundant water they must have considerable thickness, and their outcropping edges must be so situated that water may enter freely, and be replenished by rain as the water flows out at the well.

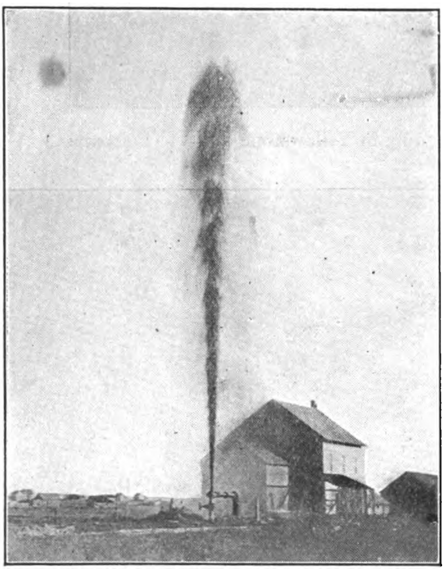


Fig. 35. Artesian well at Woonsocket, S. D. (U. S. Geol. Surv.)

A relatively imprevious layer of rock above the reservoir (*a*, Fig. 34) is most important; otherwise the water in the reservoir will leak out, and there will be little or no "head" at the well site. Thus if the rock overlying stratum *a* were badly broken, the fractures extending up to the surface, the conditions would be unfavorable for flowing wells, for though wells might get abundant water, they would not be likely to flow. If the stratum next below the reservoir is not impervious, some lower one probably is. No layer of

rock is more impervious than one which is full of water, and the substructure of any bed which might serve as a reservoir is usually full of water.

If the outcrop of the reservoir is notably above the site of the well, and if it is kept full by frequent rains, the "head" will be strong, though the water at the well will not rise to the level of the outcrop of the reservoir. Experience has shown that an allowance of about one foot per mile of subterranean flow should be made. Thus if the site of a well is 100 miles from the outcrop of the water-bearing stratum, and 200 feet below it, the water will rise something like 100 feet above the surface at the well. This rule is, however, not applicable everywhere. The failure of the water to rise to the level of its head is due chiefly to the friction of flow through the rock. The more porous the rock the less the friction. The height of the flow is also influenced by the number of wells drawing on the same reservoir, on the degree of imperviousness of the confining bed above, etc. Flowing wells, many of them relatively shallow, are frequently obtained from unconsolidated drift.

*Map work.* See Plates XC to XCIV of Professional Paper 60, U. S. Geological Survey, and Exercise IV, *The Interpretation of Topographic Maps*, a laboratory manual by Salisbury & Trowbridge.

# CHAPTER IV

## THE WORK OF RUNNING WATER

Rivers are estimated to carry about 6,500 cubic miles of water to the ocean annually.[1] Since the average height of land is nearly half a mile, the waters which flow from it to the sea fall, on the average, nearly half a mile in their flow. Their total energy is therefore great, and they are the great carriers of sediment from land to sea. The sediment which they carry is composed largely

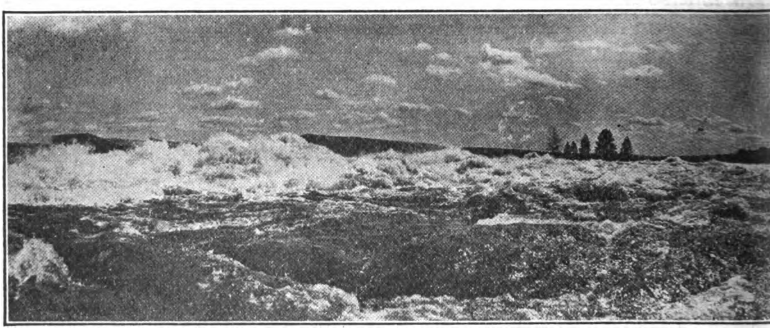


Fig. 36. Spokane River, 4 miles above Spokane, during flood. (Photo. by Tolman.)

of decayed rock, but undecayed rock is sometimes worn away, especially where streams are very swift.

Though the flow of some streams is so gentle that they do not appear to work great changes in their valleys, others wear away their banks so rapidly that the changes they produce may be seen from year to year, or, when the stream is in flood (Fig. 36), from day to day. Flooded streams occasionally sweep away dams, bridges, and buildings on their banks. The strong rods and beams of bridges and the steel rails of railways are bent almost as if they were twigs by the force of the occasional flood (Fig. 37).

[1] Murray, Scot. Geog. Mag. Vol. III. p. 70.

That the source of river water is the rain and snow which fall from the atmosphere may be inferred from various familiar phenomena. Thus (1) streams are more numerous in regions where

Fig. 37. Scene in the freight-yards of Kansas City after the flood of 1903. (U. S. Weather Bureau.)

the rainfall is abundant than in those where it is scarce (Figs. 38–39); (2) multitudes of small streams spring into being with each heavy fall of rain and with each period of rapidly melting

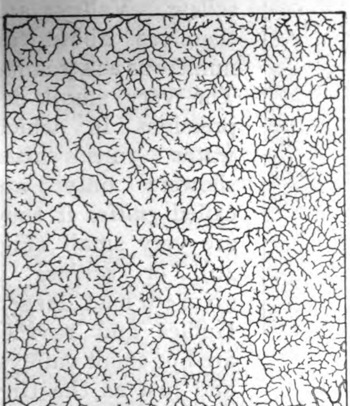


Fig. 38

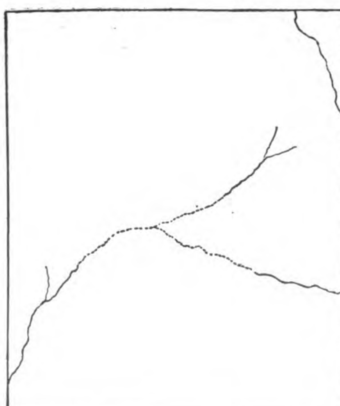


Fig. 39

Fig. 38. Map showing the many streams of a humid region. Central Kentucky. The area is about 225 square miles.

Fig. 39. Map showing the few streams of an arid region. Northern Arizona. The area is as great as that shown in Fig. 38.

snow; (3) streams are notably swollen after rains, and most after heavy ones; and (4) many small streams which flow during wet weather dry up in times of drought, while others shrink. It is true that lakes, glaciers, and springs feed the rivers, but the lakes, glaciers, and springs derive their supply of water from precipitation.

If the slope of a surface were perfectly even, the *immediate run-off* (the water which flows off without sinking beneath the surface) would flow in a sheet. There are slopes so smooth that water runs off them in this way; but on most slopes, even those which appear to be regular, there are small unevennesses, so that, although the run-off may start as a sheet, it is soon concentrated into rills and streamlets which follow the depressions. The smallest streamlets unite to form larger ones, and the little rills, after many unions with one another, reach valleys which have *permanent streams*. Streams which flow but part of the time, as after a rainstorm, during wet weather, or during but a part of the year, are *temporary* or *intermittent streams*.

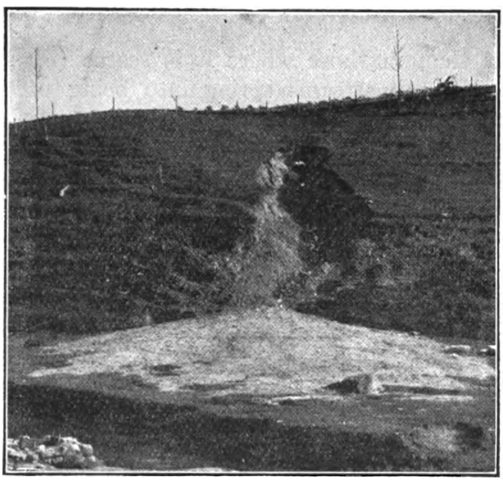


Fig. 40. A gully developed by a single shower. (Blackwelder.)

Every permanent stream and many temporary ones flow in depressions called *valleys*. Valleys are therefore about as numerous as streams. The very small depressions in which water runs after showers only are called *gullies* if they are very small (Fig. 40), or *ravines* if somewhat larger. Gullies and ravines are but small valleys, and just as the tiny streamlets unite to form creeks and these to form rivers, so the little gullies, in which the smallest temporary streams flow, generally unite to form wider and deeper ones (Fig. 41). These, in turn, join one another and become ravines, which are but larger depressions of the same sort, and ravines lead to valleys just as gullies

lead to ravines. Valleys, like streams, usually end at the ocean or a lake; but in arid regions many of them end on dry land.

There is, as a rule, some relation between the size of a valley and the stream which follows it, though this relation is not one which can be stated in mathematical terms. The large stream and the

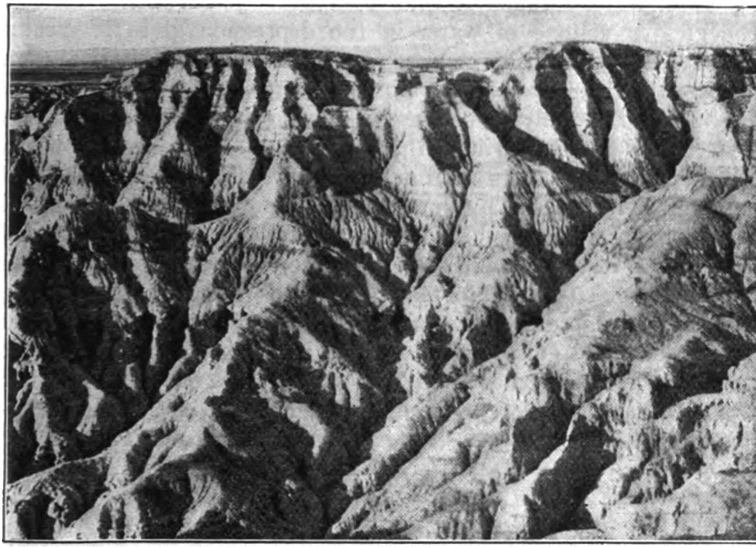


Fig. 41. Slope with numerous gullies, the smaller ones joining the larger ones. Scott's Bluff, Neb. (U. S. Geol. Surv.)

large valley go together so commonly, however, that the combination cannot be accidental.

### EROSIVE WORK OF RUNNING WATER

Wherever water flows over the land, it erodes the surface on which it flows, and the faster it flows, the greater its power of wear. The rate of flow is determined chiefly by (1) the gradient (slope), (2) the amount and especially the depth of water, and (3) the amount of sediment (load) it is carrying. The steeper the gradient, the deeper the water, and the less its load, the faster it flows. When it flows off in a sheet, as on a smooth surface, the depth of the water is slight, the flow not very swift (unless the slope is very steep), and the wear correspondingly slight. Such wear is sometimes called *sheet erosion*.

### *The Development of Valleys*

**The growth of gullies.** 1. If the slope of the surface is not uniform the effect is very different. If there is, for example, a slight depression near the base of the slope (Fig. 42), more of the descending water flows through it than over other parts of the surface. The greater volume of water in the depression gives it greater velocity; greater velocity causes greater erosion, and greater erosion deepens the depression. The immediate result is a *gully* or *wash* (Fig. 40). The gully, once started, tends to concentrate drainage in itself still more, and it is thereby enlarged. The water which enters it from the sides widens it; that which enters at its head lengthens it by causing its upper end to advance up the slope; and all which flows through it deepens it. The enlarged gully will gather more water to itself, and, as before, increased volume means increased velocity and increased erosion. As the gully grows, therefore, its increased size becomes the occasion of still further growth, and the gully is transformed into a ravine, which is no more than an enlarged gully. But growth does not stop with the ravine. Water from every shower gathers in it, and growth continues until it becomes a valley.

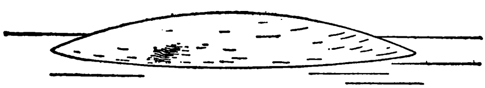


Fig. 42. Diagram showing a slight meridional depression in the surface of an otherwise even-sloped island.

It was assumed in the preceding paragraph that the single depression in the slope was meridional (Fig. 42) and low on the slope; but almost any sort of depression in almost any position would bring about a similar result, since it would lead to concentration of the run-off. Had the original surface been marked by a single ridge instead of a depression, the effect on valley development would have been much the same, for a ridge, like a depression, would cause the concentration of the run-off along certain lines, and therefore lead to the development of valleys.

Under the conditions represented in Fig. 42 the lengthening of the drainage depression is effected chiefly at its upper end, the head of the valley working farther and farther back into the land. This method of lengthening is known as *head erosion*. But the lengthening of the valley is not always wholly by head erosion. The gully begins normally where concentration of run-off begins,

and if this is not at sea-level, the gully may be lengthening at both ends at the same time. This would have been the case, for example, had the depression of Fig. 42 been half-way up the slope. Valleys developed under the control of surface slope are *consequent valleys*, and their streams are *consequent streams*.

2. If the surface material of a slope is of unequal resistance, the water flowing over it will develop irregularities of slope, even if the slope was uniform at the outset. If the material of one part of a slope is less resistant than that elsewhere, the run-off will erode most there. The depression thus started will grow, and, as before, the gully may develop into a valley. In the presence of sufficient rainfall, therefore, either heterogeneity of slope or of material will cause the development of valleys.

**The permanent stream.** It appears from the foregoing discussion that a valley may be developed by the run-off of successive showers. If supplied from this source only, surface streams would cease to flow soon after the rain ceased to fall, and a valley might attain considerable size without possessing a permanent stream. The permanent stream is, as a rule, dependent on ground-water. When a valley has been deepened until its bottom is below the ground-water surface (p. 31), water seeps or flows into it from the sides. The valley is then no longer dependent on the run-off of showers for a stream. When the bottom of a valley is below the ground-water level of a wet season, without being below that of a dry one, it will have an intermittent stream. Many valleys are now in that stage of development where their streams are intermittent.

As the valley of an intermittent stream becomes deeper, the periods when it is dry become shorter, and when it has been sunk below the ground-water level of droughts, it will have a permanent stream (3, Fig. 43). Since a valley normally develops headward, its lower and older portion is likely to have a permanent stream while its upper and younger part has only an intermittent one. So soon as a valley gets a permanent stream, the process of valley-enlargement goes on without the interruption to which it was subject when the supply of water was intermittent.

In general, a permanent stream at one point in a valley means a continuous stream from that point to the sea or lake to which the valley leads; but to this rule there are many exceptions, as where a stream heads in a region of abundant precipitation, and flows thence through an arid tract where the ground-water level is low

and evaporation great. In such cases, evaporation and absorption may dissipate the water gathered above, and the stream disappears (Pl. II). A stream like the St. Lawrence, which carries water

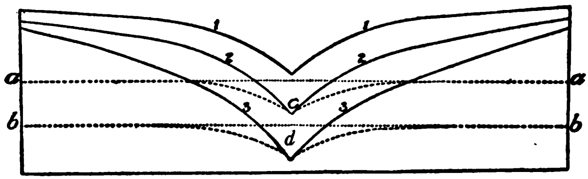



Fig. 43. Diagram to illustrate the intermittency of streams due to fluctuations of the ground-water level. The water level *aa* would be depressed next the valley 2–2, by the flow of water into the valley. The profile of the ground-water surface would therefore be *aca* and *bdb* rather than *aa* and *bb*.

from a great lake, does not depend on ground-water for its continuous flow. Again, a stream which carries the water of a melting glacier may be permanent, even though not fed by springs.

**Other modes of valley development.** Not all valleys are developed from gullies in the manner outlined above. 1. The out-

A

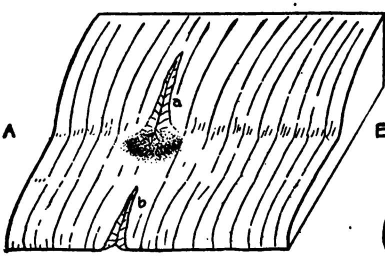



Fig. 44.

B

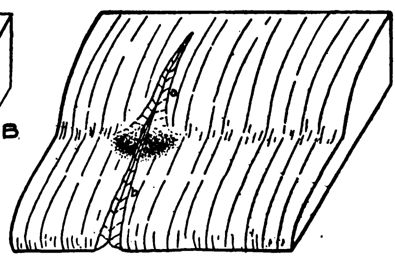



Fig. 45.

Figs. 44 and 45. Diagram to illustrate one mode of valley lengthening. In Fig. 44 there are two small valleys, *a* and *b*, and the former ends at the base of the steep slope. In Fig. 45, valley *b* is represented as having been lengthened so as to join *a*, and the two have become one.

flow of a lake would develop a valley, and the valley might be in process of excavation all the way from the lake basin to the sea at the same time. A valley developed in this manner is not simply a gully grown big by head erosion, and the valley would not precede the stream.

If a narrow coastal plain is limited landward by a steeper slope, valleys might develop as shown in Figs. 44 and 45. Again, in some mountain regions valleys are formed by the up-folding of

parallel mountain ridges, leaving a depression between (Fig. 46). Drainage will appropriate such a valley, so that it becomes in some sense a river valley; but it is not a river valley in the sense in which the term has been used in the preceding pages. It is rather a *structural valley*. A river valley may be developed in its bottom (*a*, Fig. 46) and it may be in process of development throughout the whole length of the structural valley at the same time.

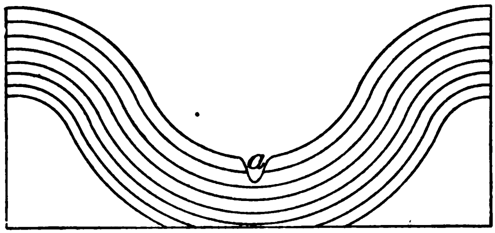



Fig. 46. Structural valley with a river valley developing in its bottom.

These illustrations do not exhaust the list of conditions under which valleys develop, but they suffice to show that valleys originate and develop in different ways.

**Limits of growth.** There are limits in depth, length, and width, beyond which a valley does not grow. A stream flowing to the sea tends to erode its valley to sea-level,[1] but actually reaches the sea-level only near the coast. In length, the valley will grow as long as its head continues to work inland. If but a single valley affected a land area, the limit in length toward which it would tend would be the length of the land area in the direction of the valley's axis. In general, valleys are limited in length by other valleys. The head of a valley works back until it reaches a point where erosion toward the valley in question is equal to erosion in the opposite direction. Here the divide becomes permanent (Fig. 47). The width of a valley is increased chiefly by the side cutting of the stream, by the wash of the rain which falls on its slopes, and by the action of gravity which tends to carry down to the bottom of the slope the material which is loosened above by any process whatsoever. The widening of valleys is limited

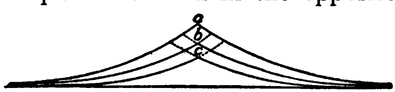



Fig. 47. Diagram to illustrate the lowering of a divide without shifting it The crest of the divide is at *a*, *b*, and *c* successively. If the erosion was unequal on the two sides, the divide would be shifted.

[1] Great rivers, like the Mississippi, cut their *channels* somewhat below sea-level, for miles above their debouchures.

much as their lengthening is. Adjacent valleys grow wider until the tops of the intervening divides are reduced to lines. Then, if erosion is equal on the two sides, the divide is lowered without being shifted in position.

**The development of tributaries.** Most considerable valleys have numerous tributaries. So soon as a gully is started, the water flowing into it from either side wears back the slopes. Any slight inequality of slope or material makes the erosion of the slopes unequal at different points, and unequal erosion in the slopes results in the development of tributary gullies. Some of these gullies develop into ravines and valleys, the same as their mains. Every new valley facilitates the run-off of the water which falls on the land, and so helps along erosion.

**Struggle for existence among valleys and streams.** It is not to be inferred that every gully becomes a valley, nor that every small valley becomes a large one. The number of little gullies which develop on a slope may be very large (Fig. 41); but the history of many of them is short. If adjacent gullies are of unequal depth, the growth of the larger finally removes the divide between them, and they become one (Fig. 48). Again, a good map of the north shore of Lake Superior or the west shore of Lake Michigan shows a large number of small valleys and gullies (Pl. III). No equal stretch of coast has so great a number of large valleys. It therefore seems evident that of these many small valleys a few only will attain considerable size.

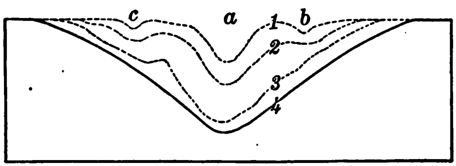


Fig. 48. Diagram illustrating how one gully takes others as a result of lateral erosion. The lines 1–4 represent, in cross-section, four stages in the development of gullies *a*, *b*, and *c*.

Some young valleys work their heads back into the land faster than others, because of inequalities of slope and material. If valleys develop in ways other than by head erosion, the chances are also against their equal growth. If two streams, such as *a* and *c*, Fig. 49, develop faster than the intermediate stream *b*, it is clear that their tributaries may work back into the territory which at the outset drained into *b*, so as to cut off the supply of water from the latter stream (compare *a′b′c′*, Fig. 50). As a result,

the growth of *b* will be checked, and ultimately stopped. Similarly other valleys, such as *f* (Fig. 49), will get the better of their neighbors, and many of the competitors, as *b′*, *d′*, *e′*, and *g′* (Fig. 50), will soon drop out of the race. Between the stronger streams

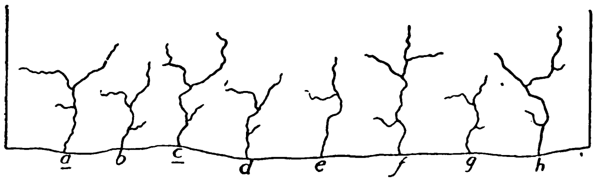



Fig. 49

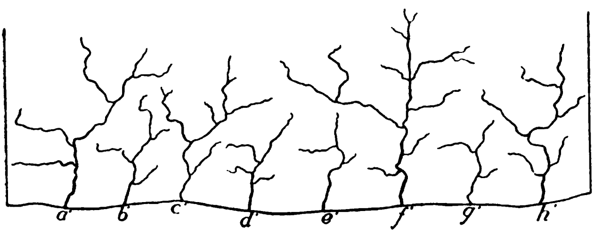



Fig. 50

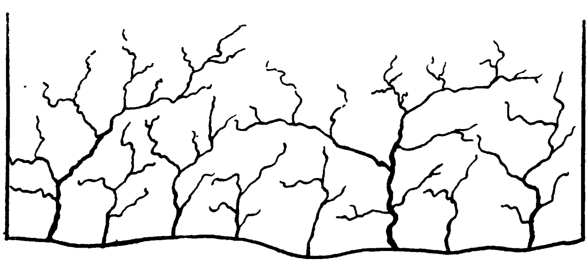


Fig. 51

Figs. 49, 50, and 51. Diagrams illustrating successive stages in the struggle for existence among streams.

competition still goes on. If *a′* and *f′* (Fig. 50) develop faster than *c′*, its prospective drainage territory will be pre-empted by them (compare Figs. 50 and 51). Thus as the result of the unequal rate at which valleys are lengthened, the larger number of those which come into existence are arrested in their development.

**Piracy.** Not all streams hold permanently the courses which they

establish for themselves in youth. Thus the Potomac Ri deepened its valley across the Blue Ridge (Fig. 52) faster t Beaverdam Creek deepened its valley. The head of the yo Shenandoah River worked back and tapped Beaverdam Cre

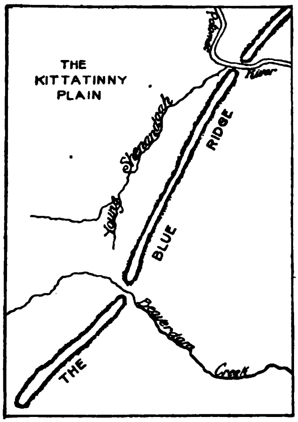



Fig. 52

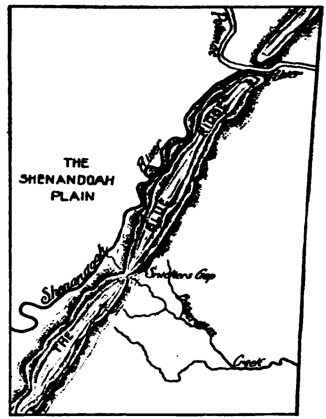



Fig. 53

Figs. 52 and 53. The capture of the head of Beaverdam Creek by the Shenandoah River. Virginia-West Virginia. (After Willis.)

*diverting* its head waters to the Potomac (Fig. 53). The Shenandoah was a *pirate*, and Beaverdam Creek was *beheaded*. The stream to which waters are diverted is increased in size, and the beheaded stream is correspondingly diminished.

### *A Cycle of Erosion*

From what has preceded it is clear that the topography of a region undergoing erosion will change greatly from time to time. The first effect of erosion by running water is to roughen the surface by cutting out valleys, leaving ridges and hills. The final effect is to make it smooth again by cutting the ridges and hills down to the level of the valley bottoms. When this has been done the plain resulting is called a *base-level.* The time necessary to produce a base-level is a *cycle of erosion.*

**Base-level, peneplain, grade.** The development of a base-level may be illustrated further in the light of the preceding discussion. Suppose a land surface affected by a series of parallel young valleys without tributaries (*a* and *b*, Fig. 54). On either side of them

there are upland plains or plateaus. The profile of the surface about two adjacent valleys is represented in cross section by the

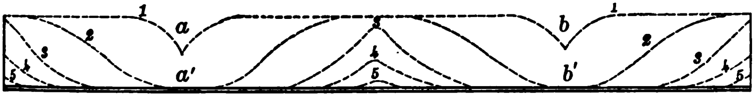



Fig. 54. Diagram to illustrate the leveling of the surface by valley erosion. The profile represented at the top shows two young valleys, 1 and 1, in an otherwise flat surface. In time these valleys will develop the cross-sections represented by 2 and 2, and later those represented by 3 and 3, 4 and 4, etc. The divide between them may finally reach 5, and the surface is then nearly flat.

uppermost line in Fig. 54. As the valleys *a* and *b* are widened to *a'* and *b'*, the adjacent uplands are narrowed correspondingly. When the valleys have attained the form represented by 3–3, the intervening upland has been narrowed to a ridge, and the valley flats have become wide. With continued erosion the ridge will be lowered still more, and in time the surface will approach a plain. In this condition it is known as a *peneplain*. When the ridges are obliterated the peneplain passes into a base-leveled plain.

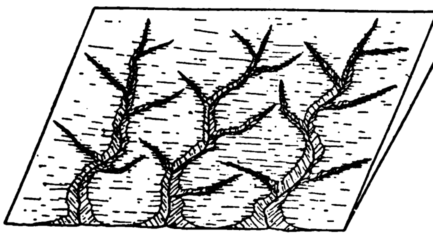


Fig. 55. Diagram showing tributaries in an early stage of development.

Tributaries are almost sure to develop along each main valley and their heads work back across the uplands between the main valleys, dissecting them into secondary ridges (Fig. 55). Tributaries develop on the tributaries, and these tertiary valleys dissect the secondary ridges into ridges of a lower order. This process of tributary development goes on until drainage lines of the fourth, fifth, sixth, and higher orders are formed (Fig. 56). Since the process of valley development under such circumstances is also the process of ridge dissection, a stage is presently reached where the ridges are cut into such short sections that they cease to be ridges, and become hills

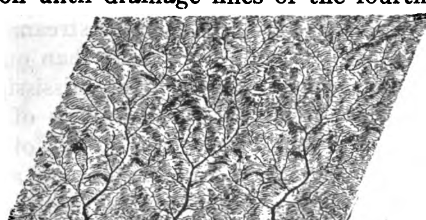


Fig. 56. Diagrammatic representation of a surface much dissected by the development of numerous tributaries.

instead. Even then the processes of erosion do not stop, for rain-water falling on the hills washes the loose material from their surfaces, and starts it on its seaward journey. Thus the "ever-lasting hills" are lowered, and, given time enough, will be carried to the sea.

The base-leveled surface is not absolutely flat. The area reduced by each stream will have a slight slope down-stream, and from its sides toward its axis. The low divides between streams flowing in the same direction may, however, disappear altogether, for when valleys have reached their limits in depth, their streams do not cease to cut laterally. Meandering in their flat-bottomed valleys, they may reach and undercut their divides (Pl. IV, and Fig. 57). By *lateral planation*, therefore, the divides between streams may be entirely eaten away.

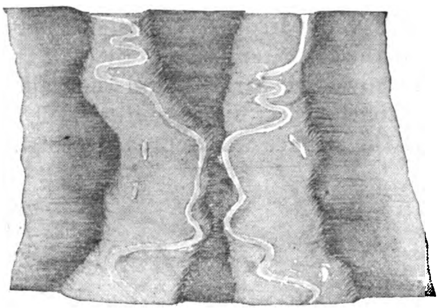


Fig. 57. Diagram showing streams in adjacent valleys, undercutting the divide between them. They may, in time, cut the divide away.

The terms "grade," and "graded plain," and "base level" and "base-leveled plain," are somewhat variously, and therefore somewhat confusingly, used. "A graded valley is one in which there is a condition of essential balance between corrasion and deposition."[1] Its angle of slope is variable and is dependent on the capacity of the stream for work, and on the work it has to do. A small river must have a higher gradient than a large one; a stream with much sediment must have a higher gradient than one with little, and a stream with a load of coarse material must have a higher gradient than one with a load of fine. Thus the graded valley of the lower Mississippi has an inappreciable angle of slope; but the graded valleys of some of its small mountain tributaries have slopes of hundreds of feet per mile. Since both the size of the stream and the amount and coarseness of its load at a given place vary from time to time in the course of a cycle of erosion, it is clear that the inclination of the graded valley in a given place must vary from time to time. With the changing conditions of

[1] Davis. Jour. of Geol., Vol. X, p. 87.

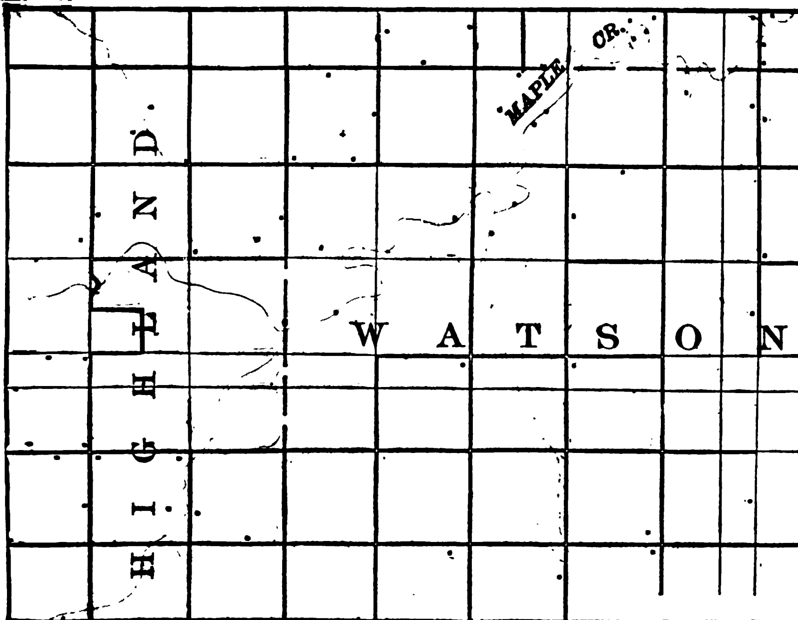



FIG. 1.—Youthful topography in a region of slight relief. The valley of Maple Creek is narrow, and much of the area is unaffected by erosion. Scale, about 2 miles per inch. Contour interval, 20 ft. (N. D., U. S. Geol. Surv.)

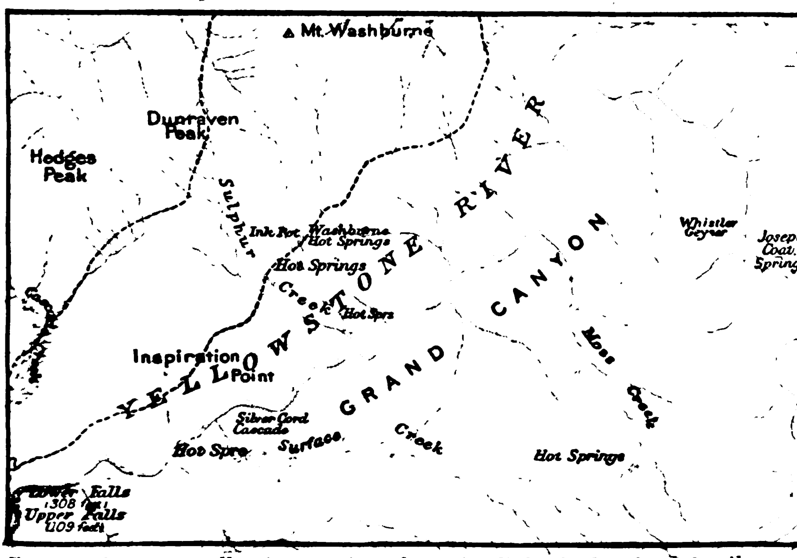



FIG. 2.—A young valley in a region of great relief. Scale, about 2 miles per inch. Contour interval, 100 feet. (U. S. Geol. Surv.)

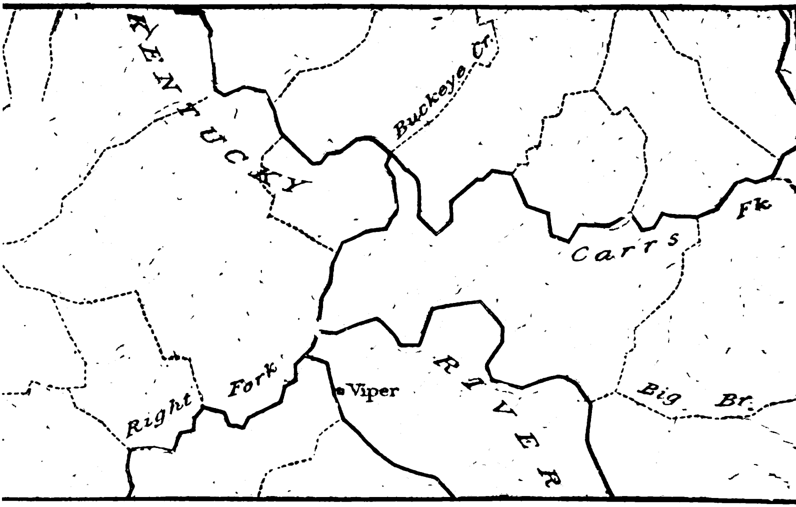



FIG. 1.—A region in a mature stage of erosion. Scale, about 2 miles per inch. Contour interval, 100 feet. (Kentucky, U. S. Geol. Surv.)

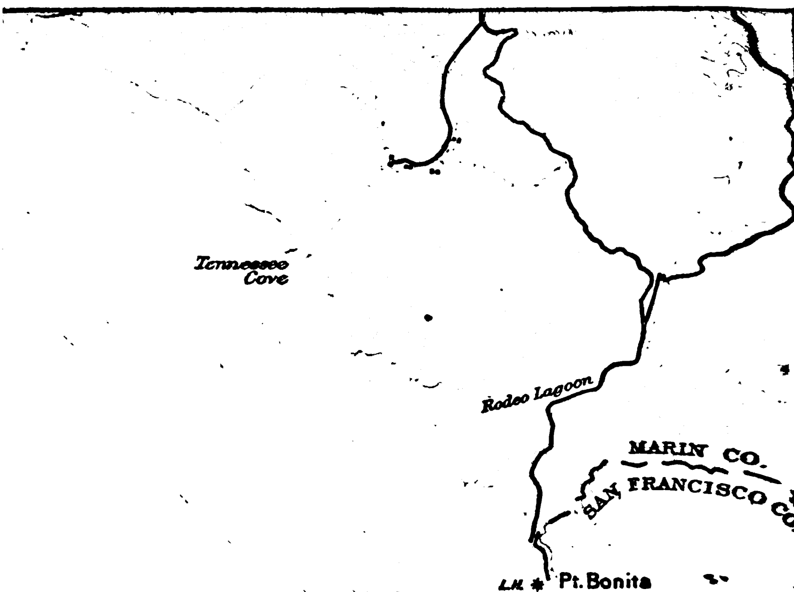



FIG. 2.—A coast line developed chiefly by wave erosion. Scale, about 1 mile per inch. Contour interval, 25 feet. (Tamalpais, Cal., Sheet, U. S. Geol. Surv.)

advancing years, the slope of a graded valley normally decreases. The same principles apply to graded surfaces outside of valleys.

When a stream has brought the bottom of its valley to grade, it may be said to be *at the level of base-level* if the gradient is low; but a *narrow* valley flat at this level is not a base-level. This term, in the sense of a base-leveled plain, is applied to extensive areas only. Any extensive area degraded by running water to essential flatness is *a base-level*. Under later conditions of erosion, even without uplift, a base-leveled surface may be reduced (slightly) to a lower base-level. There is no sharp distinction between a base-level and an extensive graded surface of low gradient, if the latter was reduced by running water.

The ocean may be looked upon as a barrier which in a general

Fig. 58. A shallow river valley in a plain. Cerro Gordo Co., Ia. Contrast with Fig. 59. (Calvin.)

way limits the down-cutting of running water. Other barriers, such as lakes, and outcrops of hard rock in a stream's bed, have a comparable, though more local and temporary, effect on the development of valley plains above themselves. Plains thus developed have been called *temporary base-levels*.

**Stages in a cycle of erosion.** Since river valleys have a beginning and pass through various stages of development before the country they drain is base-leveled, it is convenient to recognize their various stages of advancement. Nor is this difficult. An old valley and a young one have different characteristics, and the one would no more be mistaken for the other by those who have learned to interpret them, than the face of an aged man would be mistaken for that of a child.

*Youth.* The cycle begins with the beginning of valley development, and at that stage drainage is in its *infancy*. The type of the

infant valley is the gully or ravine (Fig. 40). It has steep slopes and a narrow bottom. Plate III represents somewhat older ravines, in contour. As a valley is widened, lengthened, and deepened, it passes from infancy to *youth*. In this stage also the valleys are relatively narrow, and the divides between them broad. The valleys may be deep or shallow according to the height of the land in

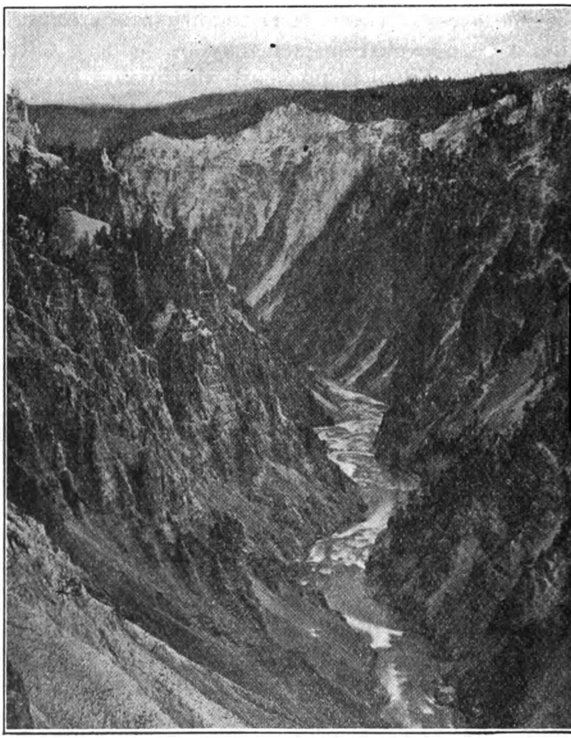


Fig. 59. Canyon of the Yellowstone below the falls. Yellowstone Park.

which they are cut, and the fall of the water flowing through them; but in any case the streams flowing through them have done but a small part of the work they are to do before the country they drain is base-leveled. Figs. 58 and 59, respectively, represent youthful valleys in regions of slight and great relief. Fig. 1, Pl. V, shows youthful valleys in a region of slight relief, and Fig. 2, Pl. V.

in a region of great relief. The uppermost line in Fig. 54 likewise represents topographic youth, as shown in cross-section.

Not only are narrow valleys said to be young, but the territory affected by them is said to be in its *topographic youth*, since but a small part of the time necessary to reduce it to base-level has elapsed. An area is in its topographic youth when considerable portions of it are still unaffected by valleys. Thus the areas (as a whole), as well as the valleys, represented on Plate V, are in their topographic youth. It is often convenient to recognize

Fig. 60. A valley much older than that shown in Fig. 59, Gray Copper Gulch, southwestern Colorado. (U. S. Geol. Surv.)

various sub-stages, such as early youth, middle youth, and late youth, within the youthful stage of valleys and topographies.

Youthful streams, as well as youthful topographies, have their distinctive characteristics. They are usually swift; their cutting is mainly at the bottom rather than at the sides, and their courses are often marked by rapids and falls.

As valleys approach base-level, they develop flats. As valleys and their flats widen, and as their tributaries increase in number and size, a stage of erosion is presently reached in which but little of the original upland surface remains. The country is reduced largely to slopes, and in this condition the drainage and the topography which it has determined are said to be *mature*. Mature topography is shown in contours in Fig. 1, Pl. VI, where slopes rather than upland or valley flats, predominate. Mature

topography is also shown in Fig. 60, which illustrates the universal tendency of rivers in regions of notable relief to develop new flats well below the former surface of the region.

The same processes which have made young valleys mature will in time work further changes. When the gradients of the valleys have become low and their bottoms wide, and when the intervening ridges and hills have become narrow and small, the drainage and the drainage topography have reached *old age*. This is illustrated by Fig. 1, Pl. VII, and in section by the third and lower lines in Fig. 54. Topographic old age may have a different expression; this

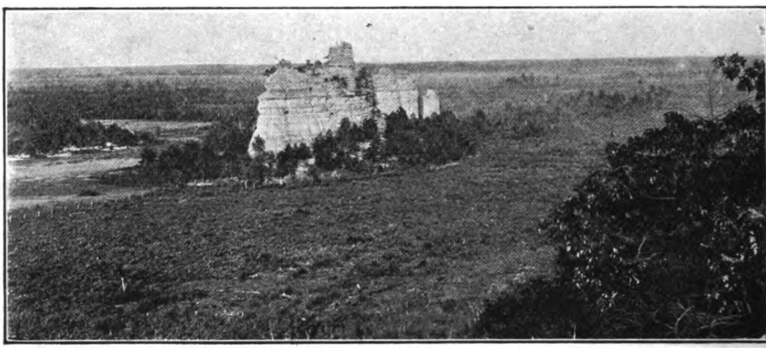


Fig. 61. A peneplain near Camp Douglass, Wis. (Atwood.)

is shown in Fig. 61, where most of the surface has been brought low. The elevations which rise above the general plain are small in area, but have steep slopes. This expression of old-age topography is usually the result of unequal resistance of the rock degraded.

The marks of old streams are as characteristic as those of young ones. They have low gradients and are sluggish. Instead of lowering their channels steadily, they cut them down in flood, and fill them up when their currents are not swollen. They meander widely in their flat-bottomed valleys (Pl. VII) and their erosion, except in time of flood, is largely lateral.

The preceding discussion, and the illustrations which accompany it, give some idea of the topography which characterizes an area in various stages of its erosion history. Whether the valleys are deep or shallow in youth and maturity depends on the height of the land and its distance from the sea. The higher the land, and

the nearer it is to the sea, the greater the relief developed by erosion. A plateau near the sea may become mountainous in the mature stage of its erosion history, while a plain in the same situation would only become hilly. A plateau in the heart of a continent would have less relief in maturity than one of equal elevation near the sea, since the grade-plain is higher in the former position than in the latter.

**Characteristics of river-shaped topographies.** With the characteristics of river valleys clearly in mind, it is easy to say whether rivers have been the chief agents in the development of a given topography. River valleys are distinguished from other depressions on land surfaces by their linear form, and, leaving out of consideration the relatively insignificant inequalities in streams' channels, by the fact that any point in the bottom is lower than any other point farther up stream in the same valley, and higher than any point farther down stream. The second point might be otherwise stated by saying that every valley excavated by erosion leads to a lower valley, to the sea, or to an inland basin. Streams which dry up, or otherwise disappear as they flow, constitute partial exceptions. If, therefore, the depressions on a land surface are linear, lead to other and deeper valleys, and finally to an inland basin or the sea, and if the elevations between these valleys are such as might have been left by the excavation of the valleys, it is clear that rain and rivers have been the chief factors in the development of the topography. If, on the other hand, a surface is characterized by topographic features which streams cannot develop, such as enclosed depressions, or hills and ridges whose arrangement is independent of drainage lines, other agents besides rain and surface streams have been concerned in its development.

*Note.* For laboratory work see p. 120.

## ANALYSIS OF EROSION[1]

Erosion is the term applied to all processes by which earthy matter or rock is loosened or removed from one place to another. It consists of several sub-processes, namely, *weathering*, *transportation*, *corrasion*, and *corrosion*.

**Weathering.** Weathering is the term applied to nearly all those

[1] An excellent discussion of this subject is given by Gilbert in The Henry Mountains, pp. 99 et seq., and more briefly in the Am. Jour. Sci., Vol. XII, p. 85, et seq., 1876.

natural processes which tend to loosen or change the exposed surfaces of rock. The inscriptions on exposed marble become fainter and fainter as time goes by, and finally disappear, because the rock in which the letters were cut has weathered away. In this case the weathering is effected partly by air and partly by water, two important agents of weathering.

The rain which falls upon the surface of exposed rock, and that which sinks through the soil to the solid rock below, dissolves slowly some of the constituents of the rock. This tends to make the rock crumble, much as mortar does when the lime carbonate which cements the sand is dissolved. The chemical changes effected by ground-water and the gases dissolved in it, also help to disintegrate the rock, as we have seen (p. 38).

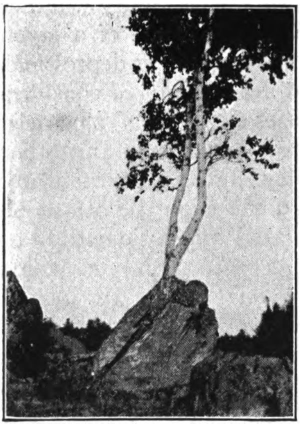


Fig. 62. Tree growing in crack in a rock, and by its growth splitting the rock.

There are processes of weathering not due directly either to the atmosphere or to water. Thus the roots of trees frequently grow in cracks of rocks (Fig. 62), and, increasing in size, act like wedges. Water freezing in cracks works in the same way. From the faces of steep cliffs masses of rock are loosened frequently by the wedge-work of roots or ice, or by expansion and contraction due to changes of temperature. The quantities of debris at the bases of many cliffs, forming slopes of *talus* (Fig. 63), testify not only to the importance of weathering, but also to the effectiveness of gravity in getting loosened material down.

The importance of weathering in erosion is shown in many ways. Where the mantle rock is the product of the decay of the solid rock beneath, and this is the case over a large part of the earth's surface, the soil and subsoil represent the excess of weathering over transportation. Since most of the earth's surface is covered with soil and subsoil, it is clear that, on the whole, weathering keeps ahead of transportation. The loosening of rock by weathering greatly increases erosion, not only by running water, but by all other agents of erosion. Though weathering is the first step in most erosion, it

Fig. 63. Talus slope, Utah.

Fig. 64. Shows the downward creep of soil and slaty rock under the influence of gravity. (U. S. Geol. Surv.)

is not the only one, and under some conditions erosion takes place without it.

**Transportation.** A second element of erosion is transportation The transportation of sediment is to be distinguished from the transportation of materials in solution. In so far as mineral matter is dissolved, it becomes a part of the fluid of the stream. The quantity dissolved is too small to influence the mobility of the water sensibly.

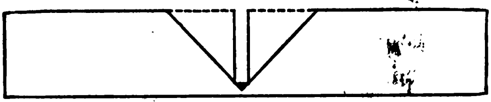


Fig. 65. Diagram of a valley, the top of which is ten times the width of the stream.

The sediment transported by a stream is either rolled along its bottom, or carried in suspension above the bottom. The coarser materials (gravel and sand) are carried chiefly in the former position, and the finer (silt and mud) largely in the latter.

*Transporting power and velocity.* The transporting power of running water depends on its velocity. Swift streams have much greater power of transportation than sluggish ones, but transportation does not always keep pace with transporting power. The Niagara at its rapids is a stream of great transporting power, but it carries little sediment, because there is little to be had.

The velocity of a stream depends chiefly on three elements — its gradient, its volume, and its load. The higher the gradient, the greater the volume, and the less the load, the greater the velocity. The relation between gradient and velocity is evident; that between volume and velocity is illustrated by every stream in time of flood, when its flow is greatly accelerated. The relation between velocity and load is less obvious, but none the less definite. Every particle of sediment carried by a stream makes a draught on its energy, and energy expended in this way reduces the velocity. A muddy stream is never so swift as a clear stream of the same size would be, flowing in the same channel.

*How sediment is carried.* Coarse materials, such as gravelstones, are rolled along the bottom of the swift streams which carry them. Their movement is by the impact of the water. The same is true to a large extent of sand grains. So far as concerns the material rolled along the bottom, it is to be noted that a stream's transporting power is dependent on the velocity of the water at its bottom, which is much less than the velocity at the surface, and less than the average velocity.

Particles of fine sediment, such as silt and mud, are carried by streams quite above their bottoms, as shown by the muddiness of many streams. Most particles of mud are small bits of mineral matter, the specific gravity of which is between two and three times that of water. Yet they do not sink through the water and come to rest at the bottom.

A particle of sediment in running water is subject to two principal forces, that of the current which tends to move it nearly horizontally down stream, and that of gravity which tends to carry it to the bed of the stream. As a result, the particle tends to move in the direction which represents the resultant of these forces (Fig. 66). If a river were the simple straightforward current which it is popularly thought to be, a particle in suspension would reach its bottom in the time it would take to sink through an equal depth of still water; for the descent would be none the less certain and scarcely less prompt because of the forward movement of the water. The current would simply be a factor in determining the position of the particle when it reached the bottom, not the time of reaching it. Very fine particles, like those of clay, sink less readily than coarser ones, because the former expose larger surfaces, relative to their mass, to the water through which they sink. But even such particles, unless of extraordinary fineness, would presently reach the bottom if acted on only by a horizontal current and gravity. Since even sediment which is not of exceeding fineness is kept in suspension, it is clear that some other factor is involved. This is found, in part at least, in the subordinate upward currents in a stream.

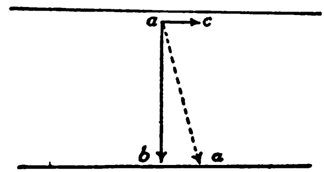



Fig. 66. Diagram to illustrate the relative strength of the two forces acting on a particle in suspension. The arrows represented by full lines show the relative strength of the two forces when the stream's velocity is about 5 miles per hour. No account is taken in the diagram of the viscosity of the water, or of the acceleration of velocity of fall.

Where a bowlder occurs in the bed of a stream (Fig. 67) a part of the water which strikes it is forced up over it. If there are many bowlders, the process is repeated frequently, and the number of upward currents is great. Any roughness will serve the same purpose, and every stream's bed is rough to a greater or less extent. Roughnesses at the sides of a channel start currents which flow

toward the center, and the varying velocities of the different parts of a stream serve a similar purpose. A river is therefore to be looked upon as a multitude of currents, some rising from the bottom toward the top, some descending from top to bottom, some diverging from the center toward the sides and some converging from the sides toward the center. The sum of the upward currents is of course always less than the sum of the downward, so that the aggregate motion of the water is down slope.

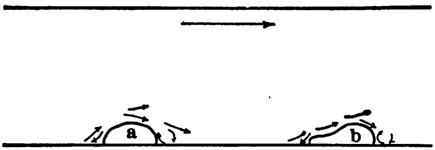



Fig. 67. Diagram to illustrate the effect of irregularities, *a* and *b*, in a stream's bed, on the current striking them.

Sediment in suspension is held up chiefly by the upward currents, which, locally and temporarily, overcome the effect of gravity. The particles in suspension are constantly tending to fall, and frequently falling; but before they reach the bottom, many of them are carried up by subordinate currents, only to sink and be carried up again. Even if they reach the bottom, as they do frequently, they may be picked up again. It is probable that every particle of sediment of such size that it would sink readily in still water is dropped and picked up many times in the course of any long river journey, and its periods of rest often exceed its periods of movement.

**Corrasion.** The mechanical wear effected by running water is *corrasion.* So long as the materials to be moved are incoherent, it is easy to understand how running water moves them. The water which flows over the surface of a cultivated field gathers earthy matter, and the process is continued all the way to the channel of the stream. Thus sediment is gathered at the very sources of flow, and the stream gathers load from its bed wherever it flows with sufficient velocity over loose material. Streams also undercut their banks, and receive new load from the fall of the overhanging material.

The larger part of the sediment of streams is made up of material loosened in advance by weathering; but many rivers wear rock which is not weathered, for the principal valleys of the earth are in solid rock, and many of them in rock of great hardness. How does the stream wear the solid rock?

When a stream flows over a rock bed, the wear which it accomplishes depends chiefly on the character of the rock, the velocity

of the stream, and the load it carries. If the rock is much divided by bedding planes and joint planes, the water of a clear stream of even moderate strength may dislodge bits of the rock. This condition of things is seen where streams run on beds of shale or slate. If the rock is hard and without bedding planes or joints, or if its layers are thick and its joints few, clear water is much less effective. If massive hard rock presents a smooth surface to a clear stream, the mechanical effect of even a swift current is slight.

This general principle is illustrated by the Niagara River. Just above the falls the current is swift. When the river is essentially free from sediment, the surface of the limestone near the bank beneath it sometimes is distinctly green from the presence of the one-celled plants (fresh-water algæ) which grow upon it. The whole force of the mighty torrent is not able to sweep them away. Were the stream supplied with a tithe of the sand which it is capable of carrying, it would not take many hours, and perhaps not many minutes, to remove the last trace of the vegetation. This illustration furnishes a clue to the method by which the erosion of solid rock in a stream's bed is effected.

The gravel rolled along the channel wears even solid rock, and as the moving stones wear the stream's bed, they are themselves worn by impact both with the bed and with one another, and are reduced to rounded, water-worn forms. The particles broken off may make grains of sand, or, if very fine, particles of silt or mud. In the course of time the pebbles and cobbles rolled along may be literally worn out.

The sediment carried in suspension, as well as that rolled along the bottom, wears the rock bed of a stream. The coarser the sediment and the stronger the current, the greater the wear. The gravel, sand, and mud carried by a stream are therefore the tools with which it works. Without them it is relatively impotent, so far as the abrasion of solid rock is concerned; with them, it may wear any rock over which it passes.

Swift and slow streams corrade their valleys differently. The erosion of a swift stream is chiefly at the bottom of its channel. The sluggish stream lowers its channel less rapidly, or not at all, and lateral erosion is relatively more important. The result is that slow streams increase the width of their valleys more than the depth, while swift streams increase the depth more than the width. It follows that slow streams develop flats, while swift ones do not.

Not only is a slow stream more likely to have a flat, and therefore a better chance to meander, but it is more likely to take advantage of opportunities in this line, for a slow stream gets out of the way for such obstacles as it may encounter, while a swift stream is much more likely to get obstacles out of its way.

**Corrosion.** In most cases the solution (and other chemical changes) effected by a stream is much less important than its mechanical work. Only when conditions are unfavorable for the latter is solution the chief factor in the excavation of a valley. This may be the case where a stream's bed is over soluble rock, such as limestone, and where the stream is clear, or its gradient so low that its current is sluggish. The solvent power of water is not influenced by the presence of sediment, though the presence of sediment offers the water a greater surface on which to work.

### CONDITIONS AFFECTING THE RATE OF EROSION

With a given amount of water, the declivity, the character of the rock, and climate, are the principal factors influencing the rate of erosion.

**Declivity.** In general, the greater the slope the more rapid the rate of erosion by running water, whether in the stream's channel or on the slopes above. But high declivity does not favor every element of erosion. It favors some phases of weathering and hinders others, but it favors both transportation and corrasion. Both corrasive power and transportive power increase rapidly with increase of velocity, and under these circumstances, corrasion also will be increased if the water has tools to work with, and transportation will be increased if there is material which can be carried. Since high declivity greatly increases both the transporting and the corrading power of running water, and favors certain elements of weathering, it is clear that its aggregate effect is to favor erosion.

**Rock.** The physical constitution, the chemical composition, and the structure of a rock formation influence the rate at which it is broken up and carried away.

*Physical constitution.* The constituents of clastic rocks may be firmly or weakly cemented. The less the coherence the more ready the disintegration, and the finer the particles the more easily they are carried away. If the materials carried are harder than the bed over which they pass, corrasion of the latter is favored.

*Chemical composition.* Something also depends on the chemical

composition of the rock, since this affects its solubility and its rate of decomposition. The more soluble the rock, the larger the proportion of it which will be taken away in solution; but it does not follow that the most soluble rock will be most rapidly eroded, since the rate of erosion depends on abrasion as well as solution, and a rock which is readily soluble, as rocks go, may be less easily abraded than one which is made of discrete and insoluble particles bound together by a soluble cement. In such rocks, for example a conglomerate in which the pebbles are cemented together by lime carbonate, the solution of the cement sets free a considerable quantity of gravel, so that a small amount of solution prepares a large amount of sediment for removal. A stream might cut its valley much more rapidly in such rock than in a compact limestone, though the latter is, as a whole, the more soluble.

*Structure.* The structure of rock has much to do with the rate of its erosion. Other things equal, stratified rock is more readily eroded than massive rock, since stratification planes are planes of cleavage, and therefore of weakness. Taking advantage of these planes, the water has less breaking to perform to reduce the material to a transportable condition. For the same reason, a thin-bedded formation is eroded more easily than a thick-bedded one.

The beds of stratified rock may be horizontal, vertical, or inclined, and inclined strata may stand at any angle between horizontality and verticality. In indurated formations the rate of erosion is influenced both by the position of the strata and by the relation of the direction of the flowing water to their dip and strike (Chapter X). In general, strata which are horizontal, or but slightly inclined, are probably less favorably situated for rapid erosion than those which are vertical or inclined at considerable angles. Joints have somewhat the effect of bedding planes, so far as erosion is concerned.

**Influence of climate.** Climate has both a direct effect on erosion, chiefly through precipitation, changes of temperature, and wind; and an indirect effect, chiefly through vegetation. Like declivity and rock structure, climate does not affect all elements of erosion equally.

*Direct effects.* The effects of variations of temperature on rock weathering have been discussed in Chapter II. Since high temperature favors chemical action, the weathering of rock by decomposition is at its best where the temperature is uniformly high, and

moisture abundant. The climatic conditions favoring chemical weathering are therefore different from those favoring mechanical weathering (p. 25).

So long as the water of the surface and that in the soil remain unfrozen, temperature affects neither corrasion nor transportation. But in middle and high latitudes the surface is frozen for some part of each year. During this time corrasion is at a minimum, for although the streams continue to flow, there is relatively little water running over the surface outside the drainage channels, and that little is relatively ineffective. Under some conditions, therefore, temperature affects both corrasion and transportation.

The humidity of the atmosphere has an influence on the rate of erosion. A moist atmosphere favors oxidation, carbonation, hydration, and the growth of vegetation, all of which promote certain phases of rock weathering. On the other hand, humidity tends to prevent sudden and considerable variations in temperature, thus checking the weathering effected by this means. Precipitation, the most important single factor in determining the rate of erosion, is dependent on atmospheric humidity. Its amount, its kind (rain or snow), and its distribution in time, are the elements which determine its effectiveness in any given place.

Other things being equal, the greater the amount of precipitation the more rapid the corrasion and transportation. Much, however, depends on its distribution in time. A given amount of rainfall may be distributed equally through the year, or it may fall during a wet season only. The maximum inequality of distribution would occur if all the rainfall of a given period were concentrated in a single shower. With such concentration the volume of water flowing off over the surface immediately after the downpour would be greater than under any other conditions of precipitation, and since velocity is increased with volume, and erosive power with velocity, it follows that the erosive power of a given amount of water would be greatest under these circumstances. Furthermore the largest proportion of the precipitation would run off over the surface under these circumstances, for less of it would sink beneath the surface, and less would be evaporated.

If erosive power and rate of erosion were equal terms, the maximum concentration of rainfall would be the condition for greatest erosion; but we have seen (p. 79) that erosive power and rate of erosion do not always correspond. If the water falling in this way

could get all the material it could carry, erosion would be at a maximum; but if the amount of material available for transportation is slight, a large part of the force of the water could not be utilized in erosion. While, therefore, it is not possible to say what distribution of rainfall favors most rapid erosion without knowing the nature of the surface on which it is to fall, enough has been said to show that the problem is not a simple one. Some of the most striking phases of topography developed by erosion, such as those of the Bad Lands (Figs. 68 and 69), are developed where the rainfall is distributed unequally in time, and too slight or too infrequent to support abundant vegetation.

Erosion in arid regions differs from that in regions of abundant rainfall in several ways. It is obvious that the valleys will develop more slowly in the former, that they will remain young longer, that the period necessary for the dissection of the surface is greater, that the water-courses will be less numerous, and that fewer of them will have permanent streams. If the arid region is high and composed of heterogeneous strata, the topography which erosion develops is more angular (Fig. 70) than that of the humid region. This is because there is less rock decay, and less vegetation to hold the products of decay. The more resistant beds of rock, therefore, come into greater prominence, especially on slopes, where they develop cliffs (Figs. 70 and 73). These general principles find abundant illustration in the plateaus of the western part of the United States,[1] where cliffs are by no means confined to the immediate valleys of the streams.

*Indirect effects.* Through vegetation, climate influences erosion in ways which are easily defined qualitatively, but not quantitatively. Both by its growth (wedge-work of roots) and by its decay (supplying $CO_2$, etc., to descending waters), vegetation favors certain phases of weathering; but, on the other hand, it retards corrasion and transportation both by wind and water. This is well shown along the banks of streams and on the faces of cliffs composed of clay, sand, etc. Its aggregate effect is probably unfavorable to erosion by mechanical means, and favorable to that by chemical processes. Winds have much to do with the rate of evaporation and the distribution of rainfall, so that their indirect effect on erosion is important.

[1] Dutton. Tertiary History of the Grand Canyon District, Mono. II, U. S. Geol. Surv.

## RATE OF DEGRADATION

The amount of mechanical sediment which the Mississippi River carries to the Gulf of Mexico was estimated many years ago to represent a rate of degradation for the Mississippi basin of about one foot in 5,000 years. But the mechanical sediment carried to the Gulf does not really represent the total degradation of the basin, for the water which sinks beneath the surface is dissolving more or less rock substance, especially lime carbonate. This material is carried to the sea in solution, and does not appear in the sediment on which the above estimate is based. More recent studies, based on fuller data, indicate that the average rate of degradation for the United States is about 1 foot in 9,000 years.[1]

The sediment carried to the Gulf by the Mississippi River is gathered from nearly all parts of its basin, but much more of it comes from some places than from others. On the whole, the rate of erosion is probably greatest toward the margins of the basin, where the land is in its topographic youth or early maturity. It is notably less in the middle courses of the valleys, and is exceeded by deposition in some places along the lower courses of the Mississippi and some of its main tributaries.

The average elevation of North America is probably not far from 2,000 feet. If it is being degraded at the rate of one foot in 9,000 years, and if this rate were to continue, it would take something like 18,000,000 years to bring the continent to sea-level. But this rate of degradation could not continue to the end, for as the continent became lower, the streams would become sluggish and erosion less rapid. Long before the continent reached base-level, the rate of degradation, so far as dependent on mechanical erosion, would become so slow that the time necessary to bring the continent to sea-level would be prolonged almost indefinitely. Furthermore, it is quite possible that the land is suffering, or is liable to suffer, uplift, relative or absolute. If the rate of rise were equal to the rate of degradation, the average height of the continent would of course not be affected.

## FEATURES RESULTING FROM SPECIAL CONDITIONS OF EROSION

Running water develops many striking topographic and scenic features. Some of them depend primarily on the conditions of

[1] Water Supply Paper 234, U. S. Geol. Surv., pp. 78–83.

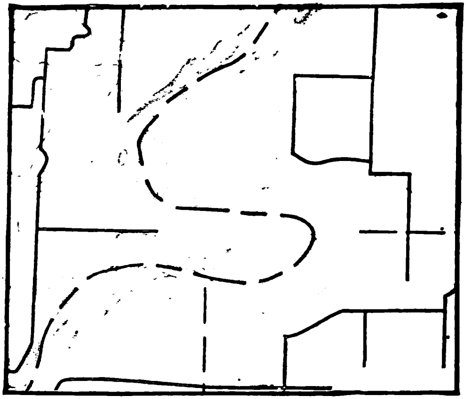



FIG. 1.—A meandering stream. The Missouri River. Scale, about 2 miles per inch. (Marshall, Mo., Sheet, U. S. Geol. Surv.)

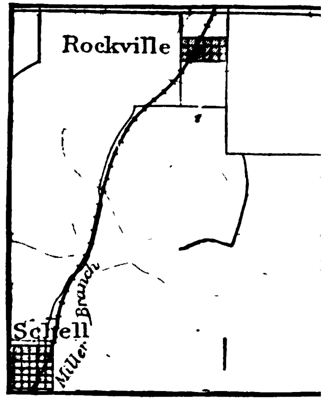



FIG. 2.—A stage in the development of a meander. Schel River. Scale, about 2 mile per inch. (Butler, Mo., Sheet U. S. Geol. Surv.)

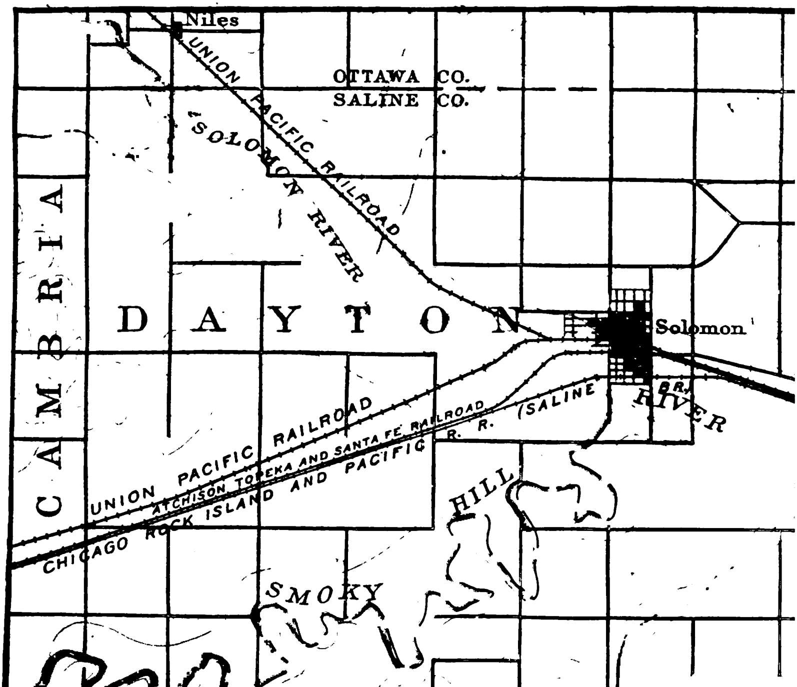
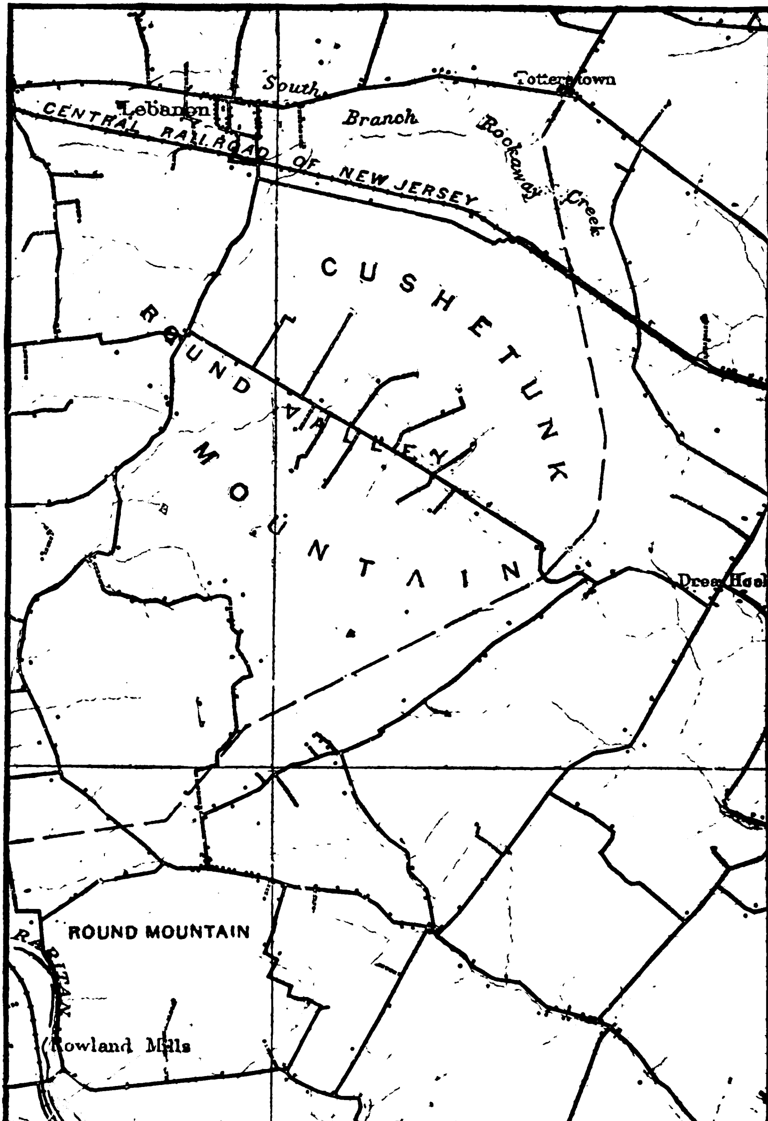



FIG. 3.—A plain in old age. Scale, about 2 miles per inch. Contour interval, 50 feet. (Abilene, Kan., Sheet, U. S. Geol. Surv.)




Cushetunk and Round Mountains, New Jersey; examples of isolated mountains left by the removal of less resistant surroundings. Scale, about 1 mile per inch. Contour interval, 20 feet. (High Bridge Sheet, U. S. Geol. Surv.)

erosion, such as climate, altitude, etc., while others depend largely on the structure and resistance of the rock.

**Bad lands.** A type of topography developed in early maturity in certain high regions where the rock is but slightly, though un-

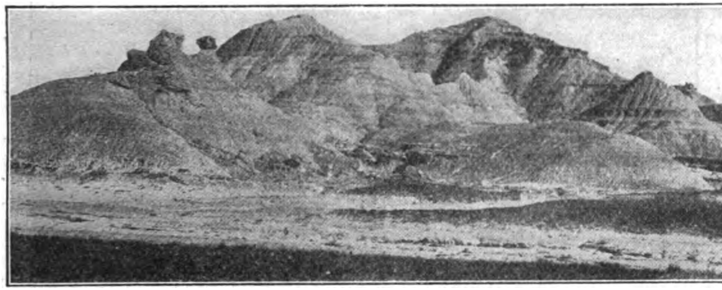


Fig. 68. Bad lands of South Dakota. Oligocene formation. (Williston.)

equally, resistant, is termed *bad-land topography* (Figs. 68 and 69). Bad-land topography is found in various localities in the West, but especially in western Nebraska and Wyoming, and the western

Fig. 69. Bad-land topography north of Scott's Bluff, Neb. (Darton, U. S. Geol. Surv.)

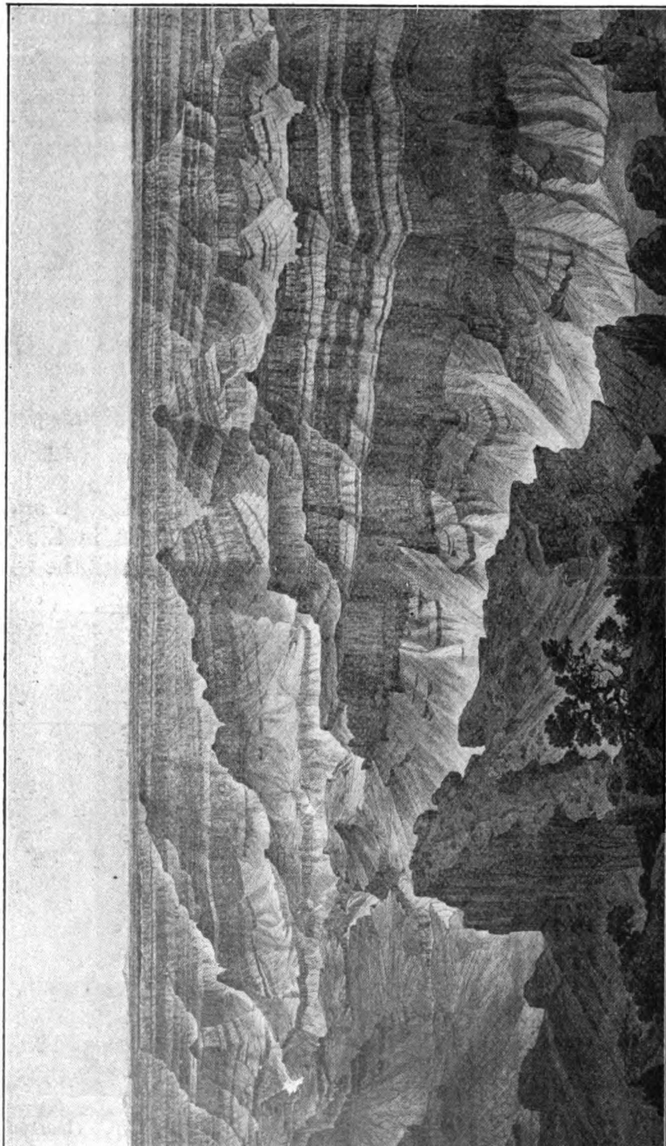


**Fig. 70.** Sketch of a part of the Grand Canyon of the Colorado. A glimpse of the river is to be had at the left. (Holmes, U. S. Geol. Surv.)

parts of the Dakotas. Many of the formations here are sandstone or shale, alternating with beds of unindurated clay. Climatic factors also are concerned in the development of this topography. A semi-arid climate, where the precipitation is much concentrated, seems to be most favorable for its development.

**Canyons.** Various conditions influence the size and shape of valleys, especially in the early stage of their development. High altitude favors swiftness of flow, and the development of deep valleys. Such valleys will be narrow if the conditions which determine widening are absent or unfavorable. An arid climate favors the development of narrow valleys if there is sufficient water to maintain a vigorous stream, because there is little slope wash.

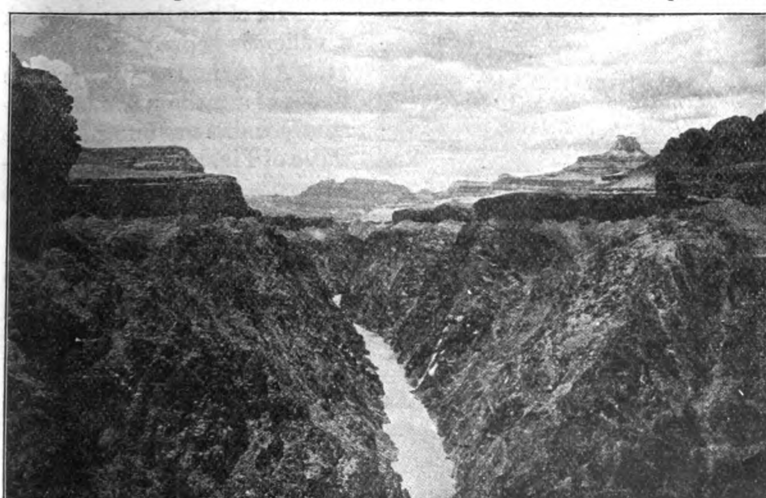


Fig. 71. Grand Canyon of the Colorado. (Peabody.)

Narrow valleys with steep slopes will also be favored if the valley is cut in rock which is capable of standing with steep faces. Thus a stream may develop a narrow valley in firm rock, where it would not do so in loose gravel. Aridity, high altitude, and the proper sort of rock structure therefore favor the development of deep narrow valleys. Such valleys are *canyons*, and many of the young valleys in the western part of the United States, where these conditions prevail, belong to this class.

While all canyons are valleys, most valleys are not canyons.

In popular usage, the rule seems to be that if a valley is sufficiently deep, narrow, and steep-sided to be distinctly striking, it is called a canyon in regions where that term is in use. Whether a valley is deep, narrow, and steep-sided enough to be striking, clearly depends on the observer. The Colorado Canyon (Figs. 70 and 71) is the greatest canyon known, but it is rarely more than a mile deep, and where its depth approaches this figure its width at the top is in most places 8, 10, or even 12 miles. Its width at bottom is little more than the width of the stream; that is, a few hundred feet. Its cross-profile throughout much of its course is therefore not in keeping with the conventional idea of a canyon. With a depth of one mile and a width of eight, the slope, if uniform, would have an angle of less than 15°. Such a valley is represented in Fig. 72. As a matter of fact the slopes of a canyon are not commonly uniform, but more like those of Fig. 73. The step-like slopes are due to inequalities of hardness. It is perhaps needless to say that to an observer on the rim of the canyon, the slopes seem several times as steep as those shown in the diagrams.

Fig. 72. Diagram showing the proportions of a valley the width of which is eight times the depth, about the proportions of the Colorado Canyon.

Like all valleys which are narrow relative to their depth, the Colorado Canyon, great as it is, is a young valley, for it represents but a small part of the work which the stream must do to bring its drainage basin to base-level.

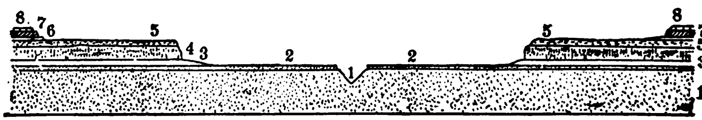



Fig. 73. Cross-section of the Colorado Canyon. (After Gilbert and Brigham.)

While aridity and high altitude are conditions which favor the development of canyons, as shown by the fact that most canyons are in high and dry regions, they are not indispensable. Niagara River has a canyon below its falls, and the surrounding region is neither high nor arid. The narrow part of the valley is so young that side erosion has not yet widened the valley or lowered its angle of slope to such an extent as to destroy its canyon character. This canyon is often called a *gorge*, a term frequently applied to small valleys of the canyon type.

## EFFECTS OF UNEQUAL HARDNESS

*Inequalities of hardness* give rise to many peculiarities of topography, and to many scenic features. To this category belong many rapids, falls, narrows, terraces, and many striking hills and ridges.

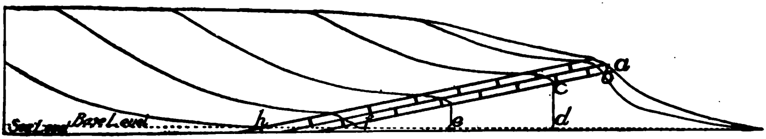



Fig. 74. Diagram illustrating the development of a fall where the hard layer dips up-stream.

**Falls and rapids.** Falls and rapids are most commonly developed where streams pass from more resistant to less resistant rock. The greater wear of the latter gives origin to rapids. At first the rapids are slight (*a*, Fig. 74), but they become more considerable (*b*) as time and erosion go on. When the bed of the rapids becomes so steep that the water *falls* (as at *cd*) rather than *flows* over the rock surface below the hard layer (*ha*), erosion assumes a new phase. The hard layer is then undermined (Fig. 76), and the undermining causes the falls to recede. This phase of erosion is sometimes called *sapping*.

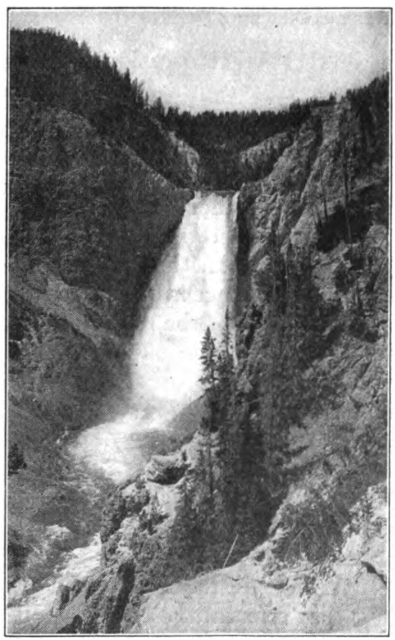


Fig. 75. Lower fall of the Yellowstone.

If the hard layer which occasions a fall dips up-stream (Fig. 74), its outcrop in the stream's bed becomes lower as the fall recedes. When it has become so low that the water passing over it no longer reacts effectively against the less resistant material beneath, sapping ceases, and the fall is then transformed again into rapids. The history of rapids which succeed falls is the reverse of the history

which preceded. The later rapids are steepest at the beginning of their history, the earlier at their end. Stated in other terms, rapids are steepest when nearest falls in time. Slight differences in the resistance of successive layers may occasion successive falls or rapids (Fig. 77).

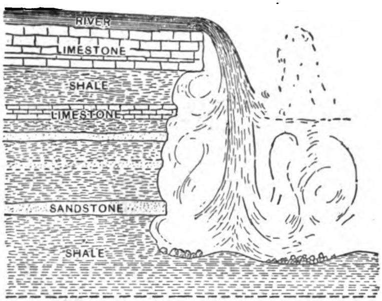



Fig. 76. Diagram illustrating the conditions at Niagara. (Gilbert.)

If the layers of unequal hardness in a stream's bed are vertical and the course of the stream at right angles to the strike, rapids, and perhaps falls, will develop. Such falls would not recede.

The inequality of resistance in the rock which occasions a fall may be original or secondary. In the case of Niagara Falls (Fig. 76) relatively resistant limestone overlies relatively weak shale. At the Falls of St. Anthony (Minneapolis) limestone overlies friable sandstone. The falls of the Yellowstone are in igneous rock. In this case the unequal resistance is caused by unequal decay of the rock, due perhaps to the rise of hot vapors which have decomposed and weakened the rock in the areas through which they have ascended. Such action is common in volcanic regions.

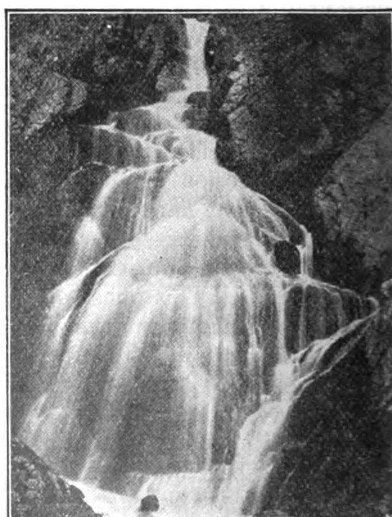


Fig. 77. Bridal Veil Fall, Kamloops, British Columbia.

One waterfall may breed others. Thus where a fall recedes beyond the mouth of a tributary stream, the tributary falls. The Fall of Minnehaha creek tributary to the Mississippi near Minneapolis, is an illustration. Once in existence, the fall of a tributary follows the same history as that of a main stream.

The fall of the Niagara [1] is one of the most remarkable known both because of its large volume of water and its great descent, between 160 and 170 feet. This fall is divided into two parts, separated by Goat Island, the Horseshoe fall (Fig. 79) on the west, and the American fall on the east. Between 1842 and 1905, the Horseshoe fall receded about five feet a year, while between 1827 and 1905, the American fall receded less than three inches a year.[1]

Fig. 78. Twin Falls, Yoho Valley, British Columbia.

**Rock terraces.** Where a hard layer outcrops in the side of a valley above its bottom, the side slopes of the valley become gentle just above the hard layer, and steep, or even vertical, at and below its outcrops, as illustrated by Fig. 80. The hard layer, H, then stands out as a rock terrace on either side of the valley. Such terraces are not rare, and are popularly believed to be old "water-lines"; that is, to represent the height at which the water once stood. In one sense this interpretation is correct, since a river has

Fig. 79. Niagara Falls. (U. S. Geol. Surv.)

[1] Gilbert, in Physiography of the United States, and Bull. 306, U. S. Geol. Surv.

stood at all levels between that of the surface in which its valley started, and its present channel; but the shelf of hard rock does not mean that the river was ever so large as to fill the valley from its present channel to the level of the terrace. Rock terraces may also result from changes of level.

**Narrows.** Where a stream crosses vertical or highly inclined strata of unequal resistance, its valley is usually constricted at the crossing of the hard layers. If such a constriction is notable it is called a *narrows*, or sometimes a *water-gap* (Fig. 81). The Appalachian Mountains afford numerous examples. The narrows develop because the processes which widen the valley are less effective on more resistant rock than on less resistant. Some narrows arise in other ways also.

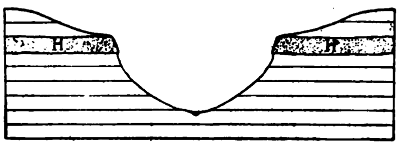



Fig. 80. Rock terraces due to a resistant layer, H, of rock.

Narrows are much more conspicuous in certain stages of erosion than in others. While a valley is still so young as to be narrow at all points, there can be no pronounced "narrows"; but later, when the valley is elsewhere wide, narrows become pronounced. From what has preceded it is clear that rapids or falls are likely to occur at narrows, especially early in their history.

**Other effects.** Inequalities in the hardness of rock develop certain peculiarities of topography outside of valleys. The less

Fig. 81. The Kittatinny Mountain and Delaware Water-Gap from Manunka Chunk. (N. J. Geol. Surv.)

resistant portions of a land area more or less distant from streams are worn down more readily than those which are more resistant. If great areas of high land are capped with hard rock, they are likely to remain high after surrounding areas of less resistance are brought low. If the hard capping remains over a small area instead of a

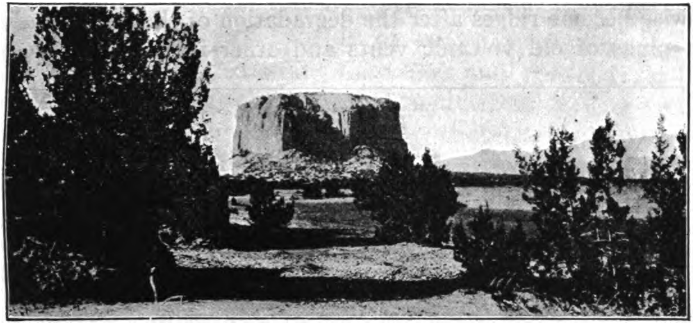


Fig. 82. The Enchanted Mesa. A striking butte in New Mexico. The name mesa is not commonly applied to elevations of such small summit area. (R. T. Chamberlin.)

large one, the elevation is a butte, a hill, or a ***mountain***; if over a large area, a plateau. Many buttes and small mesas are but remnants of former plateaus. A feature of buttes and mesas capped

Fig. 83. Hogbacks; Sec. 22, T. 16, N., R. 112 W., Wyoming. The rock which occasions the hogbacks is the Lazeart sandstone at the base of the Adaville formation. (Veatch, U. S. Geol. Surv.)

by hard rock is the steep slopes or *cliffs* corresponding to the edges of the hard beds (Figs. 70 and 82).

If the rock of a region is stratified and the layers tilted, the removal of the softer beds leaves the harder ones projecting above the general level in the form of ridges or "hog-backs" (Fig. 83). Dikes of igneous rock, harder than the beds which they intersect, likewise become ridges after the degradation of their surroundings. The plugs of old volcanic vents and other igneous intrusions of

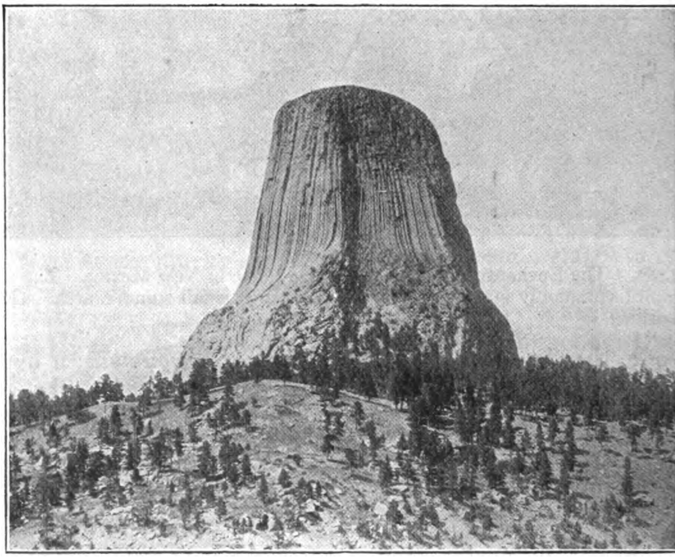


Fig. 84. A monadnock; a mass of intruded igneous rock isolated by erosion, and remaining high because of its superior hardness. Matteo Tepee, Wyo. (Detroit Photo. Co.)

limited area may constitute conspicuous hills or mountains (Fig. 84) after erosion has removed their less resistant surroundings. Cushetunk Mountain, Pl. VIII, is an example.

Ridges and hills resulting from the unequal degradation of unequally resistant strata are most prominent in the late maturity or early old age of an erosion cycle. The outcropping masses of hard rock are then more perfectly isolated than at earlier stages. Most of the even-crested ridges of the Appalachian system, as well as many others which might be mentioned, became ridges in this

way. In the final stages of an erosion cycle, the ridges of hard rock are themselves brought low. Isolated remnants of hard rock which remain distinctly above their surroundings in the late stages of an erosion cycle are known as *monadnocks*, the name being derived from Mount Monadnock, N. H., an elevation of this sort developed in a cycle antedating the present.

### THE EROSION OF FOLDS

The erosion of folded strata (*anticlines* and *synclines*) leads to the development of distinctive topographic features. So soon as a fold begins to be lifted, it is, by reason of its position, subject to more rapid erosion than its surroundings. For the same reason, the crest of a fold is likely to be degraded more rapidly than its lower slopes, and must suffer more degradation before it is brought to base-level. Most folds are composed of beds of unequal resistance, and as their degradation proceeds, successive layers are worn from the top, and the alternating layers of more and less resistant rock are exposed. The less resistant beds are worn down faster than the others, and in time the outcrops of the stronger beds become ridges, distinctly above the outcrops of the weaker beds which have become valleys and lowlands (Fig. 85).

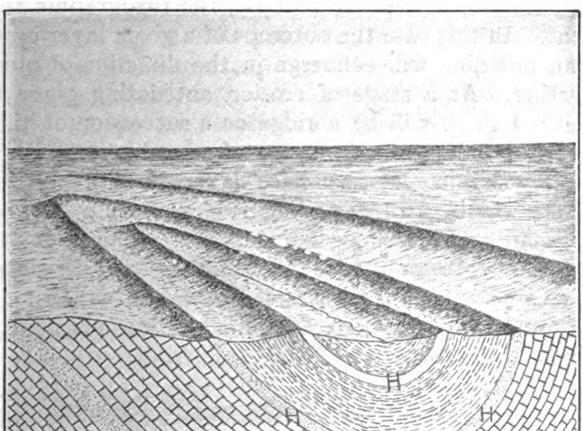


Fig. 85. A canoe-shaped valley bordered by a ridge formed by the outcrop of a hard layer in a plunging syncline. The ridge bounding the canoe-valley is separated from an outer ridge by a curved valley, underlain by relatively weak rock. (Willis.)

If the axis of an eroded anticline were horizontal, a given hard layer, the arch of which has been cut off, would outcrop on both sides of the axis. When the topography has become mature, these outcrops will constitute parallel ridges, or parallel lines of hills. When the region had been base-leveled, the outcrop will be in parallel belts, though no longer ridges or hills. The lower the plane of truncation, the farther apart the outcrops will be in the

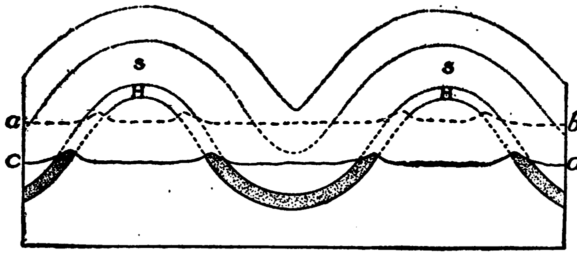



Fig. 86. Diagram showing the outcrops of hard layers (shaded) on the flanks of truncated folds; *cd*, present surface; *ab*, an earlier erosion surface.

anticline, and the nearer together in the syncline (compare outcrop of H, along *ab* and *cd*, Fig. 86).

If, on the other hand, the axis of the anticline or syncline is not horizontal, that is, if it *plunges* (dips), the topographic result will be different. In this case the outcrops of a given layer on opposite sides of an anticline will converge in the direction of plunge, and come together. At a stage of erosion antedating planation (say late maturity) there will be a ridge or a succession of hills, in the position corresponding to the outcrop of a hard layer, with a canoe-shaped valley within. If two hard layers are involved, instead of one, there will be two encircling ridges, with a curved valley between them, and a canoe-shaped valley within the innermost (Fig. 85). A succession of plunging anticlines and synclines might give rise to a very complex series of ridges and valleys. Illustrations of the above phenomena are found at various points in the Appalachian Mountains.[1]

Fig. 87. Cross-section of a portion of the Appalachian Mountains to illustrate the relations of mountain ridges to anticlines and synclines, and the phenomena of erosion cycles. (Rogers.)

[1] Willis, The Northern Appalachians, in *Physiography of the United States.*

In the structural adjustment which goes with the erosion of folds, it happens in many cases that valleys come to be located on the anticlines after the latter have been worn down, while the outcrops of the hard layers on the flanks of the anticlines, or even in the original synclines, become the mountains (Fig. 87).

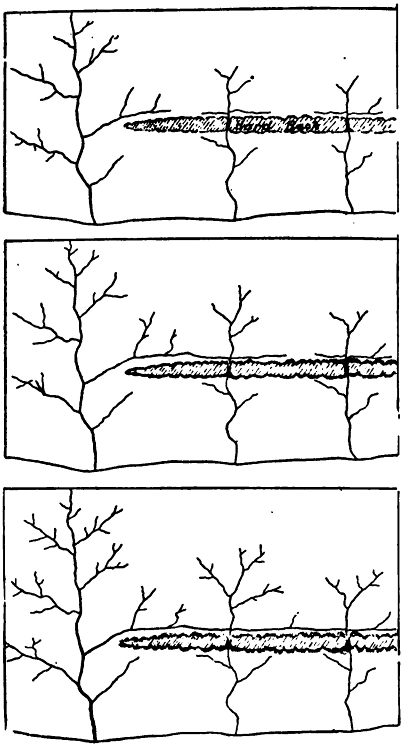
### ADJUSTMENT OF STREAMS TO ROCK STRUCTURES

Valleys (gullies) are located at the outset without immediate regard to the hardness and softness of their beds. It is primarily the slope about the head of a gully which determines its line of growth, and, once established, streams tend to hold their courses; but the streams on the weaker rock will deepen their valleys more rapidly than others, and have an advantage over them. Being deeper, their tributaries may be lengthened until their heads reach the other valleys, with the results shown in Figs. 88–90. Even where several streams cross the same resistant bed, piracy is likely to take place among them, for some are sure to deepen their valleys faster than others, because of inequalities of volume, load, or hardness. This is illustrated by Figs. 91–93. (See also Figs. 52 and 53.) Piracy may take place where streams do not flow over rock of unequal resistance, but it is more common where they do, for greater resistance of rock puts the stream which crosses it at a disadvantage as compared with the stream which crosses less resistant rock.

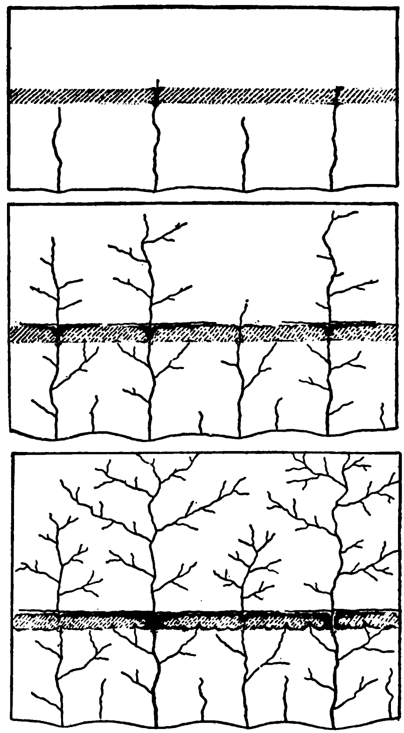
The changes in the courses of streams by means of which they come to sustain definite and stable relations to the rock structure beneath, are known as processes of *adjustment*.[1] Since streams and valleys adjust themselves to other conditions as well, this phase of adjustment may be called *structural adjustment*. Structural adjustment is not uncommon among rivers flowing over strata which are vertical or highly inclined, since in these positions, strata of unequal resistance are most likely to alternate with one another at the surface. The processes of adjustment go on until the streams flow as much as possible on the weaker beds, and as little as possible on the stronger. Adjustment is then complete. This amounts to the same thing as saying that the outcrops of resistant layers tend to become divides. In many cases an area is so situated that there is no escape for its drainage except across resistant rock. In this case drainage is completely adjusted when as few streams as possible cross the resistant rock, and these by the shortest routes.

[1] Campbell, Jour. Geol., Vol. IV., pp. 567, 657.

Adjustment has been carried to a high degree of perfection in many parts of the Appalachian system. Here, as in all other mountains of similar structure, strata of unequal hardness were folded into ridges. The folds were then truncated by erosion,



Figs. 88–90.



Figs. 91–93.

Figs. 88–90. Diagrams illustrating piracy, where the stream which does not flow over rock of superior hardness captures those which do. Fig. 89 represents a further development of the drainage shown in Fig. 88, and Fig. 90 represents a still later stage.

Figs. 91–93. Diagrams to illustrate piracy where the competing streams all cross a hard layer. The diagrams represent successive stages of development.

exposing the more and the less resistant beds (*H* and *S*, Fig. 86, respectively) in alternate belts along the flanks of the truncated folds (truncated at *ab* and *cd*). The streams, especially the lesser ones, now flow along the strike of the weaker beds much more

commonly than elsewhere, and where they cross the hard layers it is in most cases at right angles to the strike. This is shown in Fig. 94, where the arrows indicate the direction of strike.

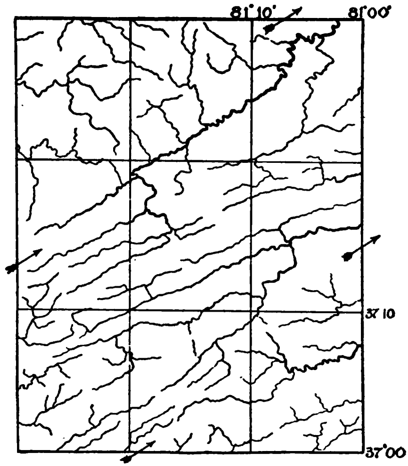



Fig. 94. Adjusted drainage in a region of folded rocks. The many nearly parallel streams are flowing with the strike.

As base-level is approached, the outcrops of hard rock are brought low. When the resistant beds have been reduced to base-level, streams may flow without regard to the resistance of the rock beneath, for downward cutting has ceased.

It happens in some cases that rocks of unequal resistance are covered by beds of uniform hardness. A consequent stream (p. 61) developed on the latter may find itself out of structural adjustment when its channel is sunk to the level of the heterogeneous beds below. Such a stream is said to be *superimposed* (Fig. 95) on the underlying structure. Structural adjustment is likely to follow in time.

### INFLUENCE OF JOINTS ON EROSION

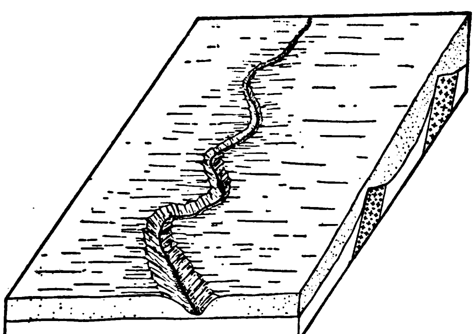


Fig. 95. Diagram to illustrate superimposition. The consequent stream on the upper formation was superimposed on the underlying structures when the upper bed had been cut through.

It has been pointed out that joint planes have somewhat the same influence upon erosion that bedding planes have when the beds are tilted at a high angle. Most rocks are affected by joints, and many of them are nearly vertical. Two sets are generally present, and in some places more. When there are but two, they usually meet at a large angle (Fig. 2). These

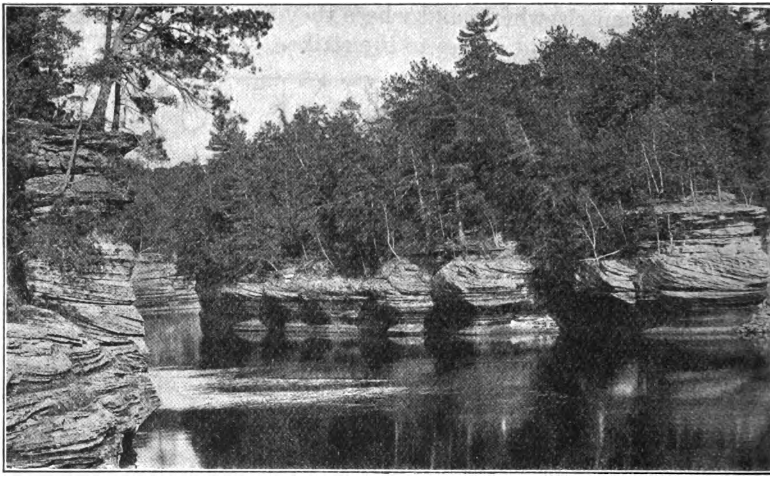


Fig. 96. Figure showing crenate river bank, the re-entrants being determined by joints. Dells of the Wisconsin River, near Kilbourn, Wis. (Atwood.)

joints allow the ingress of water, roots, etc., which help to weather and disrupt rocks. Their effect on erosion may be seen along many streams which flow in rock gorges. In such situations, the outlines of the banks are in some cases angular, and in some crenate (Fig. 96), the re-entrants being located at the joints. By working into and widening joints, running water in some places isolates masses of rock as islands (Fig. 97).

Fig. 97. An island formed by river erosion in jointed rock; Lower Dells of the Wisconsin. (Atwood.)

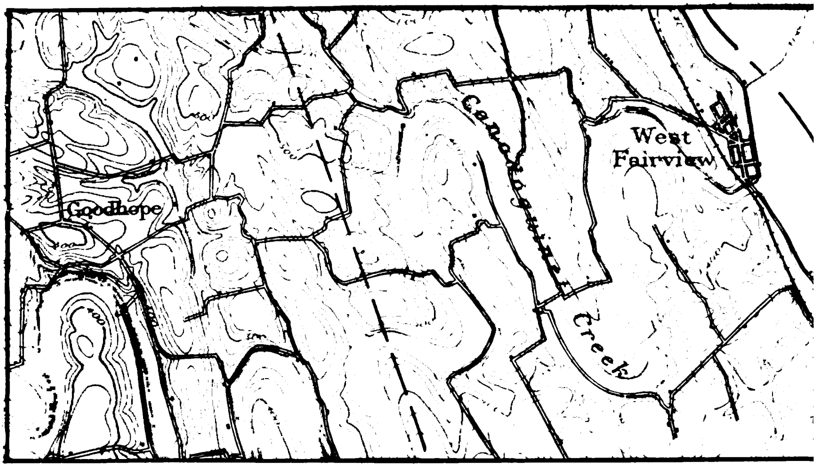



FIG. 1.—Entrenched meanders. Scale, about 1 mile per inch. Contour interval, 20 feet. (Harrisburg, Pa., Sheet, U. S. Geol. Surv.)

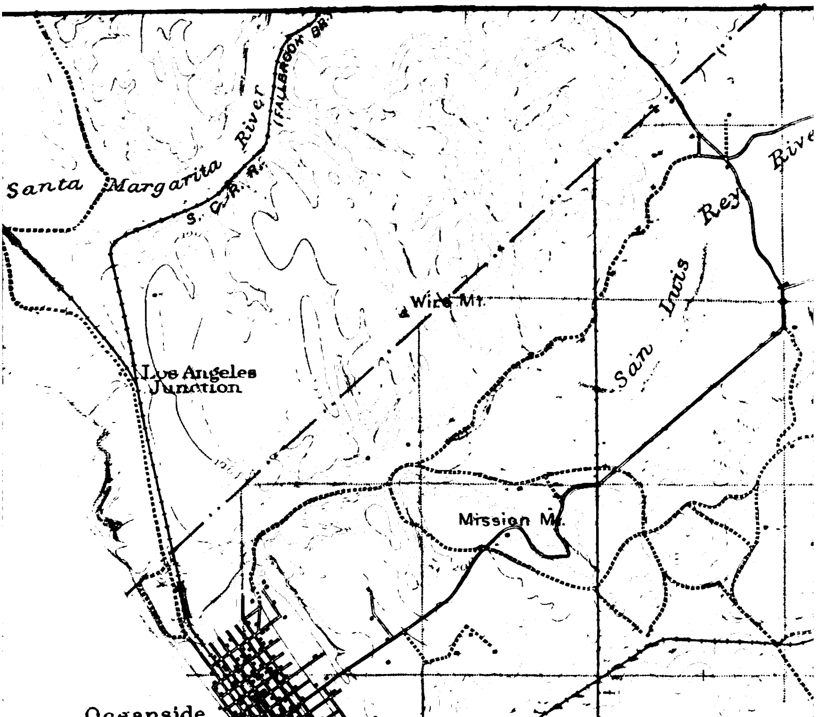
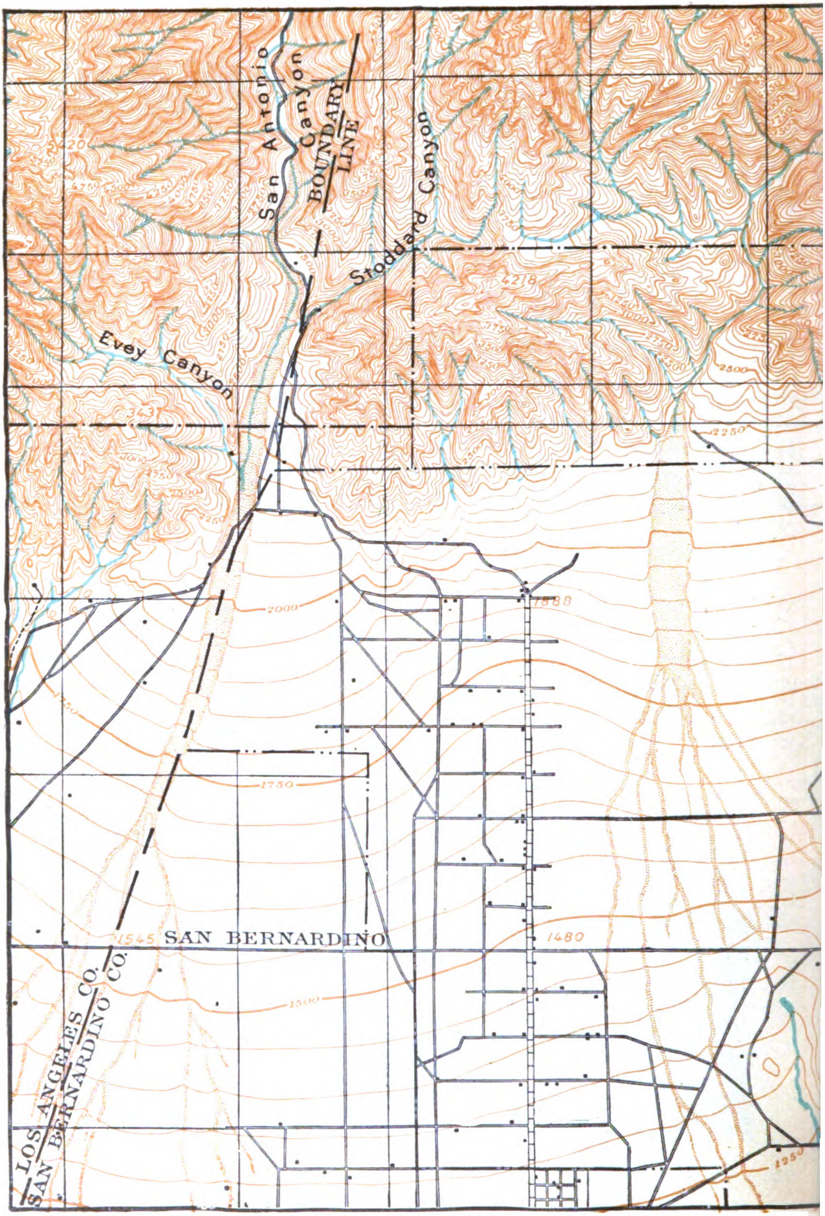



FIG. 2.—A Section of the California Coast, showing lands near the coast, which have recently emerged. Scale, about 1 mile per inch. Contour interval, 20 feet. (Oceanside, Cal., Sheet, U. S. Geol. Surv.)

PLATE X




A piedmont alluvial plain or compound alluvial fan in Southern California.
Scale, about 1 mile per inch. (Cucamonga, Cal., Sheet, U. S. Geol. Surv.)

In a region free from mantle rock, or where the mantle rock is meagre, joints have determined the courses of many valleys by directing the course of surface drainage. This is well shown in many parts of the arid West. In regions where the rocks are faulted the courses of some streams are controlled by the faults. It is probable that joints and fault planes have been more important in locating valleys, especially where the mantle rock is thin, than was formerly recognized.

Joints in rocks may occasion the development of natural bridges. If above a waterfall, for example, there is an open joint in the bed of the stream (as at *b*, Fig. 98), some portion of the water will descend through it. After reaching a lower level it may find or make a passage through the rock to the river at the falls. If even a little water takes such a course, the flow will enlarge the passageway through the joint to the valley at the falls (*bcde*, Fig. 98). This passageway may in time become large enough to accommodate all the water of the river. The entire fall will then be transferred from the position which it previously occupied (*f*) to the position of the enlarged joint (*b*). The fall will then recede. The underground channel between the old falls and the new will then be bridged by rock (*bf''* and *f'''*, Fig. 99). The natural bridge near Lexington, Va. (Fig. 100), almost 200 feet above the stream which flows beneath it, is believed to have been developed in this way. It is not to be understood that all natural bridges[1] have had this history.

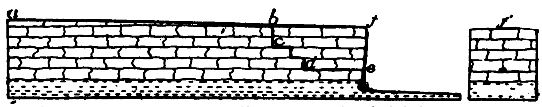



Fig. 98. Diagram to illustrate the initial stage in the development of a natural bridge. Longitudinal section at the left, cross-section at the right.

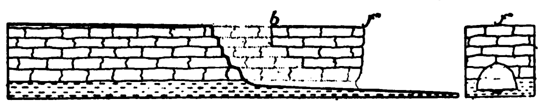



Fig. 99. A stage later than that shown in Fig. 98.

## EFFECT OF CHANGES OF LEVEL

**Rise.** If, after being base-leveled, or notably advanced in an erosion cycle, a region is uplifted so as to increase the gradients and velocities of its streams, they are said to be *rejuvenated*. Renewed youth differs from first youth, in that the streams

[1] Cleland, Pop. Sci. Mo., May '11, and Bull. G. S. A., Vol. XXI, p. 313.

are already in existence. The rejuvenated streams erode their valleys after the manner of youthful streams. They excavate new valleys in the bottoms of older ones (Figs. 101 and 102), deepening them until they reach the new grade plane. Young valleys in the bottoms of old ones are one of the evidences of rejuvenation. The new valley in the old one may be developing all along its course at the same time, or it may begin at the debouchure of a stream and work headward. In either case, the tributaries are rejuvenated when their main is lowered at the point of union.

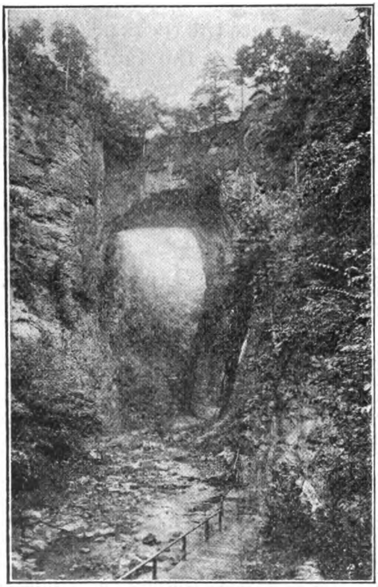


Fig. 100. The Natural Bridge of Virginia. (U. S. Geol. Surv.)

Another evidence of rejuvenation is found in entrenched meanders. When an old winding stream is rejuvenated, the deepened channel follows the course of the stream before rejuvenation. The result is that a new winding gorge is cut; that is, the old meanders are *entrenched*. Entrenched meanders are rather common in the Appalachian Mountains (Fig. 1, Pl. IX), and are known in other parts of the world.[1] With rejuvenation of the drainage, a new cycle of erosion is begun, whether the preceding one was complete or not.

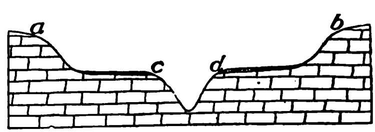



Fig. 101. Cross-section of a wide valley, *ab*, in the bottom of which a younger valley, *cd*, has been excavated, as the result of uplift.

The principles involved in the recognition of cycles of erosion, separated by uplifts, are illustrated by Fig. 103, which represents an ideal profile of considerable length (say 20 miles). The points $a$, $a'$, and $a''$ have about the same elevation. Below them there are areas $b$, $b'$, and $b''$, which

[1] Davis. The Seine, the Meuse, and the Moselle. Nat. Geog. Mag., Vol. VII, pp. 181–202, and 228–238.

have a nearly common elevation, below which are the sharp valleys $d$, $d'$, and $d''$. The points $a$, $a'$, and $a''$ represent the tops of ridges formed by the outcrops of layers of hard rock. If the crests of the ridges are level, the points $a$, $a'$, and $a''$ must represent remnants of an old base-level, *since at no time after a ridge of hard rock becomes deeply notched does it acquire an even crest, until it is base-leveled.*[1] After the cycle represented by the remnants $a$, $a'$, and $a''$ was completed, the region suffered uplift. A new cycle represented by the plain $b$, $b'$, and $b''$ was well advanced, though not completed, when the region was again elevated, and the rejuvenated streams began to cut their valleys $d$, $d'$, and $d''$ in the plain of the previous incomplete cycle. The elevations, $c$ and $c'$ (intermediate between $a$, $a'$, and $a''$, and $b$, $b'$, $b''$), may represent either remnants of the first base-level plain, lowered but not completely removed while the plain $b$, $b'$, $b''$ was developing; or they may represent a cycle intermediate between that during which $a$, $a'$, $a''$ and $b$, $b'$, $b''$ were developed.


Fig. 102. Diagram to illustrate an ideal case of rejuvenation as the result of uplift. The black area at the bottom represents the sea.

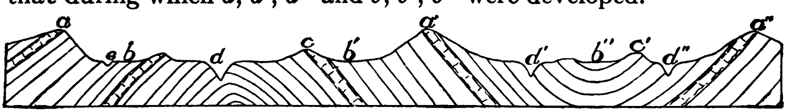



Fig. 103. Diagram to illustrate cycles of erosion where the beds are tilted.

If the strata involved are horizontal, the determination of cycles may be less easy. Thus in Fig. 104, it is not possible to say whether $a$ and $a'$ represent remnants of an old base-level, or whether they represent the original surface from which degradation started. So, too, the various benches below $a$, such as $b$, $b'$, and $b''$, might well be the result of the superior hardness of beds at this level. For the determination of successive cycles in the field, it is necessary

[1] Other views have been entertained. See Tarr, Am. Geol., Vol. XXI, pp. 351–370, and Daly, Jour. of Geol., Vol. XIII, pp. 105–125.

to consider areas of considerable size, and to eliminate the topographic effects of inequalities of hardness.

It is by the application of the preceding principles that it is known that the Appalachian Mountains, after being folded, were reduced to a peneplain (the Kittatinny peneplain) from the Hudson River to Alabama. The old peneplain surface is indicated by

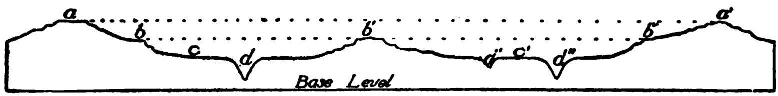



Fig. 104. Diagram to illustrate cycles of erosion where the beds are horizontal.

the level crests of the Appalachian ridges. The system was then warped (not folded) up, and in the cycle of erosion which followed, broad plains were developed at a new and lower level, corresponding in a general way to the plains *b*, *b'*, and *b''* of Fig. 103. The plains were located, for the most part, where the less resistant strata come to the surface. Above them rise even-crested ridges, the outcrops of the resistant layers, isolated by the degradation of the weaker beds between. It is the outcrops of these layers which constitute many of the present mountain ridges corresponding to the high points of Fig. 103. The evenness of their crests testifies to the completeness of the first peneplanation. The evenness of the crests is, however, interrupted (1) by notches cut by the streams in later cycles, and (2) by occasional elevations (monadnocks) above the common level. Most of the monadnocks are rather inconspicuous, but there is a notable group of them in North Carolina and Tennessee, of which Mount Mitchell and Roan Mountain are examples. When long distances are considered, the ridge crests depart somewhat from horizontality. This is believed to be due, in part at least, to deformation of the old peneplain during the uplift which inaugurated the second cycle of erosion.

The extent to which the second cycle of erosion recorded in the present topography had proceeded before its interruption by upwarp is indicated by the extent of the valley plains (Fig. 103) below the mountain ridges. While these plains were being developed on the weak rocks, narrow valleys (*water-gaps*) only were cut in the resistant rocks which stood out as ridges. Similar valleys, whether shallow or deep, from which drainage has been diverted, are sometimes called *wind-gaps*.

The second cycle of erosion, still incomplete, was interrupted by

uplift (relative or absolute), and a third cycle was inaugurated. The third cycle began so recently that it has not yet advanced far.

Some of the features just described are illustrated by Fig. 81. The even mountain crest in the background is the Kittatinny Mountain of New Jersey and its continuation in Pennsylvania. In common with other corresponding crests, it is a remnant of the oldest recorded base-level (or peneplain) of the region. Below the mountain crest there is another plain, developed in a subsequent cycle of erosion, while the valley plain in the foreground represents the work of a still later cycle.

Many of the peculiarities of the drainage of the Appalachian Mountain system are intimately connected with the history just outlined. Thus three great rivers, the Delaware, the Susquehanna, and the Potomac, have their sources west of the Appalachians proper, cross the system in apparent disregard of the structure, and flow into the Atlantic. The James and Roanoke head far to the west, although not beyond the mountain system, and flow eastward, while the New River (leading to the Kanawha) farther south, heads east of the mountain-folds, and flows northwestward across the alternating hard and soft beds of the whole Appalachian system, to the Ohio. The French Broad, a tributary to the Tennessee, has a similar course. Such streams are clearly not in structural adjustment, and afford good opportunities for piracy. Their courses were apparently assumed during the time of the Kittatinny peneplain, when the streams had so low a gradient as not to be affected by structure. Elevation rejuvenated them, and they have held their courses in succeeding cycles across beds of unequal resistance, though smaller streams have become somewhat thoroughly adjusted. Crustal deformations have also helped them to hold their courses, for the peneplain seems to have been tilted to the southeast at its northern end, and to the southwest at its southern, when the succeeding cycle began.

Streams which hold their early courses in spite of changes which have taken place since their courses were assumed are said to be *antecedent*. They antedate the crustal movements which, but for pre-existent streams, would have given origin to a different arrangement of river courses. As a result of crustal movements, therefore, a consequent stream may become antecedent. Master streams are more likely to hold their courses, and therefore to become antecedent, than subordinate ones.

The uplift of base-leveled beds, especially if the beds are tilted so as to bring layers of unequal resistance to the surface at frequent intervals, affords conditions favorable for extensive adjustment. The numerous wind-gaps in the mountain ridges, representing the abandoned courses of minor streams, and the less numerous water-gaps, which indicate the resistance of large streams to structural adjustment, are instructive witnesses of the extent to which adjustment has gone. So extensive has it been among the streams of the Appalachian Mountains that there is probably no considerable stream in the whole system which has not gained or lost through its own or its neighbors' piracy.

**Sinking.** The land on which a river system is developed may be depressed relative to sea-level. In this case the sea occupies the lower ends of valleys, converting them into bays and estuaries. A valley in this condition is said to be *drowned*. Of drowned valleys there are many examples along the Atlantic coast. Thus

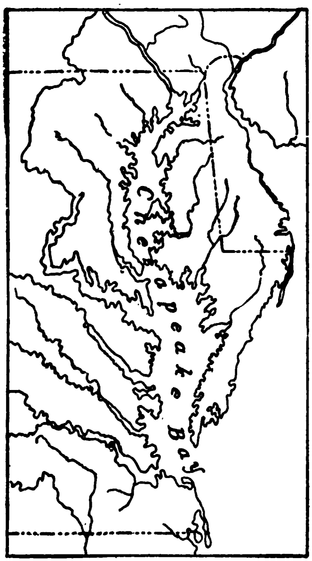


Fig. 105

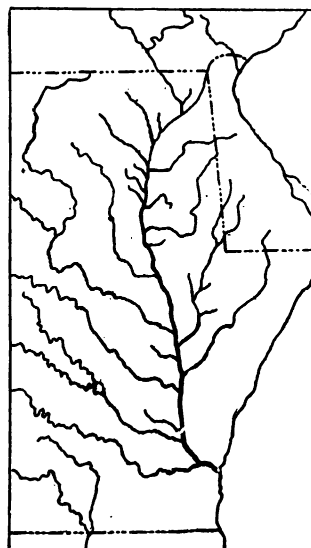


Fig. 106

Fig. 105. Chesapeake Bay and its surroundings. The bay is a drowned river valley, and the lower ends of its tributary valleys are also drowned.

Fig. 106. The drainage of the region about Chesapeake Bay as it would have been but for drowning.

the St. Lawrence is drowned up to Montreal, and the Hudson up to Albany. If the drowned portion of the latter valley were not so narrow, it would be a bay. Delaware and Chesapeake bays, as well as many smaller ones, both north and south, are likewise the drowned ends of river valleys (Figs. 105 and 106).

**Successive rising and sinking.** Another peculiarity of valleys and streams resulting from changes of level is illustrated by Pl. IX, Fig. 2. The main valleys of this part of the coast were developed when the land stood higher than now. Later, the sinking of the coast converted the lower ends of the valleys into bays. The bays were then transformed into lakes or lagoons by deposition at their mouths. Subsequent rise of the land or sinking of the sea allowed the drainage from the lakes to cut across the deposits which had converted the bays into lakes. The result is an older, wider valley above, succeeded by a younger one near the debouchure.

**Differential movement. Warping.** A land surface on which a river system is established may suffer warping, some parts going up and others down. Above an upwarp which notably checks its flow, a stream is *ponded*. If a stream holds its course across a notable uplift athwart its valley, it becomes an antecedent stream. The Columbia River has been thought to hold its antecedent course across areas which have been uplifted (differentially) hundreds and even thousands of feet.[1] A lesser stream would have been diverted, as many of its tributaries have been.

## AGGRADATIONAL WORK OF RUNNING WATER

We have seen that rivers carry mud, sand, gravel, etc., from land to sea, and that their goal is the degradation of the land to base-level. We have seen also that rivers do not always carry their sediment directly to the sea. In many cases it is dropped for a time on land, perhaps to be picked up and carried on again when conditions for its transportation are more favorable. We have now to inquire more particularly into the causes and results of deposition.

**Causes of deposition.** When running water drops its load, or any part of it, it is generally because the current has lost velocity. Decrease of gradient is the commonest cause of loss of velocity. The loss may be (1) sudden, as when the water passes from a steep slope to a gentle one, or into a body of standing water; or (2) slow, as in following a valley whose gradient decreases gradually. We

[1] Russell. Rivers of North America, p. 279.

therefore look to the places where these changes in velocity occur for the principal deposits of running water. Streams also become slower wherever their channels become wider, even if volumes and gradients remain constant.

Decrease of volume is a less common cause of decrease of velocity. Most streams increase in size as they flow, but to this general rule there are exceptions. (1) If a stream flows through a very dry region it receives few tributaries, while evaporation is great and the thirsty soil and rock through which it flows absorb some of its water. In such a region a stream may diminish as it flows, and may even disappear altogether (Pls. II and X). (2) In some places certain streams break up into several (Fig. 107), and in this case the volume and therefore the velocity of each is less than that of the original stream. (3) Many streams, especially in arid regions, have much of their water withdrawn for irrigation. (4) During the decline of their floods, all streams decrease in volume and velocity.

Fig. 107. Delta of Lake St. Clair. (Lake Survey Chart.)

### *Location and Forms of Alluvial Deposits*

1. **At bases of steep slopes.** The water of every shower washes sediment down the slopes of hills, and much of it is left at their bases. Its lodgment there, even where there are no valleys or gullies, is shown in some places by the burial of fences by the mud lodged against them. Temporary streams flowing down steep slopes are checked suddenly at their bases, and abandon there their heavy loads of debris. Thus, at the lower end of the new-made gully on the hillside there is commonly a mass of detritus which was washed out of the gully itself (Figs. 40 and 108). Material in such positions accumulates in the form of a partial cone, known as an *alluvial cone*. Alluvial cones have much in common with cones

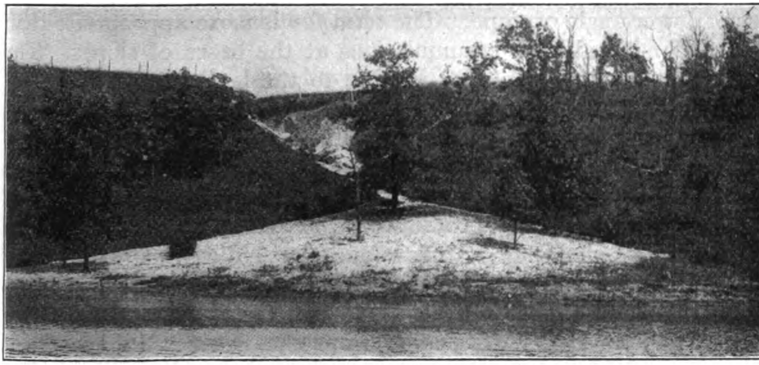


Fig. 108. An alluvial cone. (U. S. Geol. Surv.)

of talus. In the latter, gravity brings the material down with little aid from water, but between the two types of cones there are all gradations.

Conspicuous alluvial cones are common at the bases of steep slopes in semi-arid regions. The rainfall there is fitful, and the

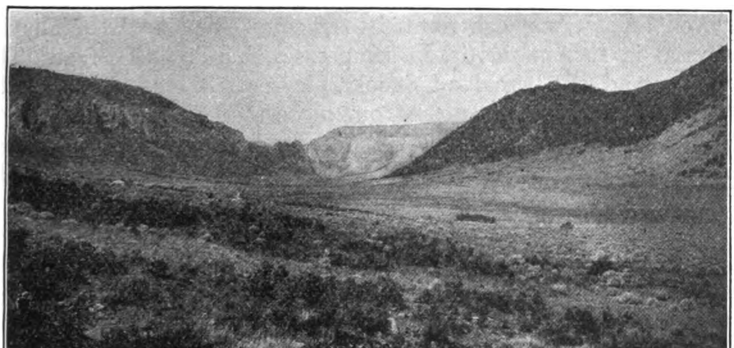


Fig. 109. Deposition at the bases of valley slopes, tending to give the valley a U-shaped base. Unaweep Canyon, Colorado. (Cross, U. S. Geol. Surv.)

occasional heavy showers, which give rise to temporary and powerful torrents, favor the development of great cones. At the bases of the mountain ranges in the Great Basin, some of the talus and alluvial cones are 2,000 or 3,000 feet high.

An *alluvial fan* is the same as an alluvial cone, except that it

has a lower angle of slope. The term *fan* is more appropriate than *cone* for most alluvial accumulations at the bases of slopes. The lower angle of the fan may be due to the less abrupt change of slope where it is developed, to the larger quantity of water concerned in its deposition, to the smaller amount of detritus, or to its greater fineness. Less change of slope, more water, and less and finer material, all favor the wider distribution of the sediment, and so the development of fans rather than cones. Nearly all young rivers descending from mountains build fans where they leave the mountains. Thus, the rivers descending from the Sierras to the great valley of California build great fans at the base of the range. Many rivers descending from the Rockies to the Great Plains have done the same thing. The fans of some streams descending from the mountains are many miles across. That of the Merced River in California, for example, has a radius of about 40 miles.

The fans made by neighboring streams may spread laterally until they merge. The union of such fans makes a *compound alluvial fan*, or a *piedmont alluvial plain* (Pl. X). Such plains exist at the bases of most considerable mountain ranges. Sheet wash, as well as streams, contributes to them. The depth of alluvial material in such plains is, in some cases, hundreds of feet. The great spread of these land deposits is remarkable. East of the Rocky Mountains they extend out more than a hundred miles in some places. This wide spread appears to be the result of the long-continued action of running water. The cone or fan, as first built,

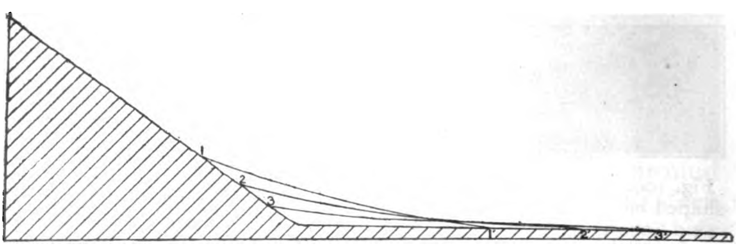


Fig. 110. Diagram to illustrate the spreading of alluvial deposits in a piedmont position. The deposits may first take the position represented by the line 1–1′. At a later stage, as a result of erosion and redeposition, they take the position represented by the line 2–2′, being spread farther from the mountain and having a lower surface slope. At a still later time, they take the position 3–3′, with a still lower slope and a still wider spread.

is degraded later, and its materials spread more widely, as suggested by Fig. 110.

Deposits of this sort have probably been far more important in the past than has been generally recognized. Much of the material of the Coastal Plain of the Atlantic and Gulf slopes of the United States appears to have been deposited in this way. A large part of the Great Plains is covered with wash from the Rocky Mountains, and similar deposits are of great extent and depth east of the Andes and south of the Himalayas. They are, indeed, of significant extent and depth on the plains about almost every mountain range which has been carefully studied. It seems clear that similar deposits must have been made at all stages in the past history of the earth, whenever and wherever mountainous lands bordered plains.

Formations of this general sort, made at the bases of high lands, have now been recognized among the ancient formations of the

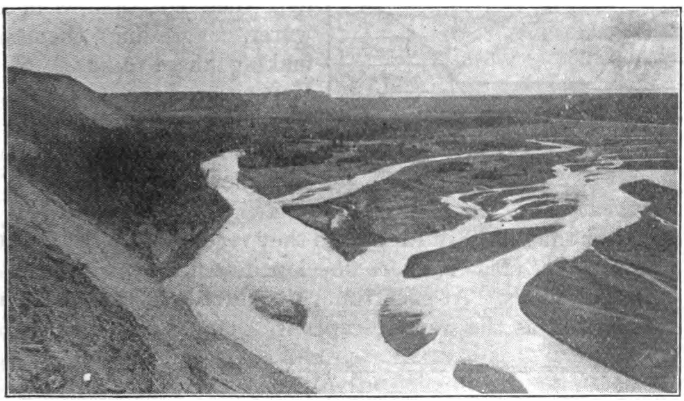


Fig. 111. A branching stream. Junction of the Cooper and Yukon rivers, Alaska. Shows also bars, etc. (U. S. Geol. Surv.)

earth, as well as among the recent ones, and some of the ancient beds of sediment deposited in this way attained thicknesses of hundreds and even thousands of feet. They probably attained their greatest thickness, as now, in basins.

2. **In valley bottoms.** A stream which makes deposits in its channel, makes the channel smaller. In time it may become too small to hold all the water. A part then breaks out, and follows

a new course over the valley flat. This process may be repeated again and again (Fig. 111). Some streams deposit bars in their channels, especially in low water. The bars may be swept away in time of flood, but some of them become more or less permanent islands.

The profiles of the bottoms of most valleys are curves, the curvature becoming less as the lower end of the stream is approached


Fig. 112. Profile of a normal valley, showing decreasing slope down stream.

(Fig. 112). It therefore happens that as a stream descends its valley it generally reaches a point where its reduced gradient so diminishes its velocity that it must abandon some of its load. In this way sediment is distributed for long distances along valley bottoms. It is left in the channels of streams in low water, and spread over their flood plains in high water, aggrading them and making them *alluvial plains*. Deposition in a valley which has no flat tends to develop one (Fig. 113). Alluvial deposits on valley flats are usually but a few feet, or at most a few scores of feet thick; but in rare cases they reach hundreds of feet.

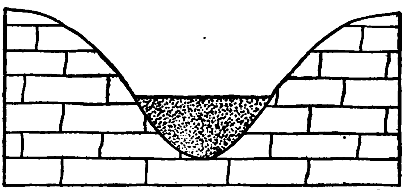


Fig. 113. Flat developed by aggradation — diagrammatic.

*Natural levees* (Fig. 114) are developed on flood plains aggraded by occasional floods. At such times the current in the main channel is swift; but as the water escapes its channel and spreads over

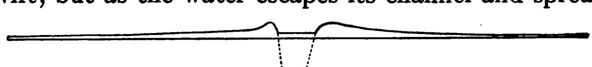


Fig. 114. Levees of the Mississippi in cross-section, four miles north of Donaldsonville, La. Vertical scale ×50. The horizontal line represents sea-level. The bottom of the channel is far below sea-level at this point.

the adjacent flat, its velocity is checked promptly, because its depth suddenly becomes less. It therefore abandons much of its load then and there. Repeated deposition in this position, in excess of that over other parts of the flood plain, gives rise to the levees.

*Scour-and-fill.*[1] Aggrading streams deepen their channels period-

[1] Hill, Erosion and Deposition by the Indus. Geol. Mag., July, 1910.

ically to a notable extent, and the deepening of the channel takes place at the very time when the flood-plain is being aggraded. In other words, the stream in flood aggrades its plain, and degrades its channel. This follows from the fact that the current is slow on the plain, where the water is shallow, and rapid in the channel, where it is deep. After the flood subsides, the channel, deepened while the current was torrential, is filled up again by sediment from

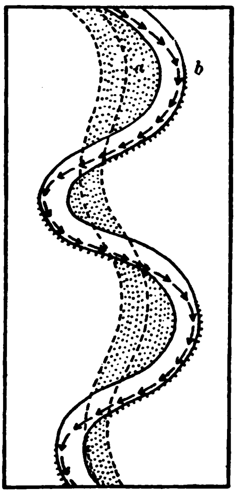



Fig. 115

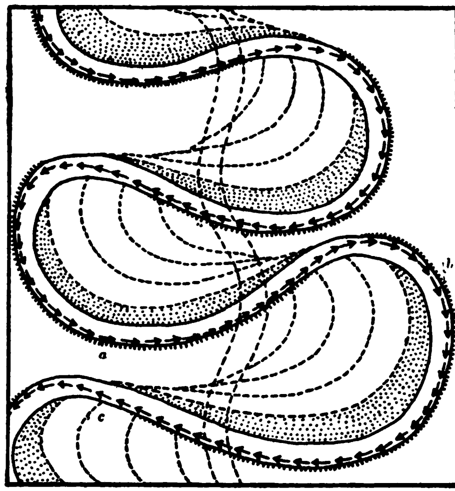



Fig. 116

Fig. 115. Diagram illustrating an early stage in the development of river meanders. The dotted area represents the area over which the stream has worked.
Fig. 116. A later stage in the development of meanders.

the feebler current. This alternate deepening and filling is *scour-and-fill*. It is well illustrated by the Missouri River. At Nebraska City, scour reaches depths of 70 to 90 feet occasionally. At Blair, about 25 miles above Omaha, the same river is believed to cut to bed-rock (about 40 feet below the bottom of the channel in low water) during floods. All streams similarly situated do a like work. The material thus eroded is shifted down-stream, some of it for short distances only, and some of it to the sea. An aggrading stream, therefore, is not without erosive activity; it is a stream whose fill exceeds its scour, not one which has ceased to erode.

**Materials of the flood-plain.** As a result of its varying velocities in flood and low water, a stream may deposit coarse material at

one time and fine at another. Many flood-plain deposits are, therefore, very heterogeneous, ranging from the finest mud, through sand, to gravel, and even bowlders. In general they become finer down-stream.

**Flood-plain meanders.** A stream with an alluvial plain is likely to meander widely (Pls. XI and VII). In general terms this may be said to be the result of low velocity, which allows the stream to be turned aside easily. Were the course of such a stream made straight, it would soon become crooked again. The manner of change is illustrated by Figs. 115 and 116. If the banks are less resistant at some points than at others, as is always the case, the stream will cut in at those points. If the configuration of the channel is such as to direct a current against a given point, *b* (Fig. 115), the result is the same, even without inequality of material. Once a curve in the bank is started, it is increased by the current which is directed into it. Furthermore, as the current issues from the curve, it impinges against the opposite bank and develops a curve at that point. The water issuing from this curve develops another, and so on.

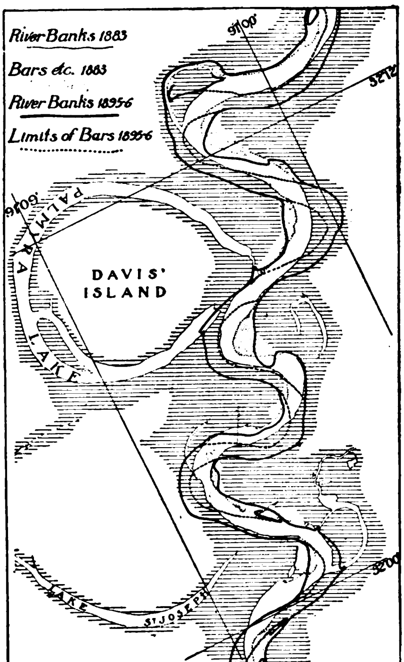



Fig. 117. Meanders and cut-offs in the Mississippi Valley below Vicksburg. The figure shows the migration of the meanders down stream, and their tendency to increase.

Once started, the curves or meanders tend to become more and more pronounced (Fig. 116). In the case represented by Fig. 1, Pl. VII, the narrow neck of land between curves is almost cut through. A later stage in the process is shown in Fig. 2. When the stream has cut off a meander, the abandoned part of the channel may remain unfilled with sediment. If it contains standing water, as many do, it becomes a lake (Fig. 117). Some such lakes

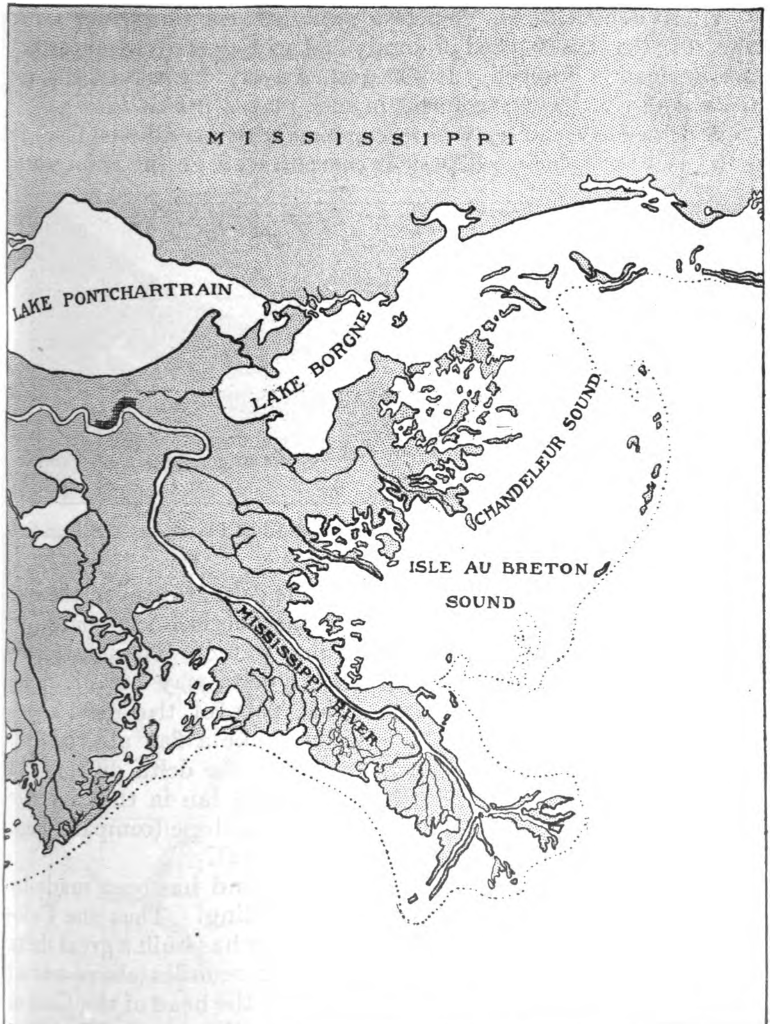



Fig. 118. Delta of the Mississippi. The dotted line outside the land represents the 3-fathom line.

have the form of an oxbow, and so are called *ox-bow lakes* (Fig. 117, and Pls. VII and XI).

3. **At debouchures.** Where a swift stream flows into sea or lake, its current is checked promptly and soon destroyed altogether, and its load is dropped. If not washed away by waves, etc., the deposits of river-borne sediment in such places make *deltas*.

A delta has some features in common with an alluvial fan. In both cases the principal deposit is concentrated at the point where

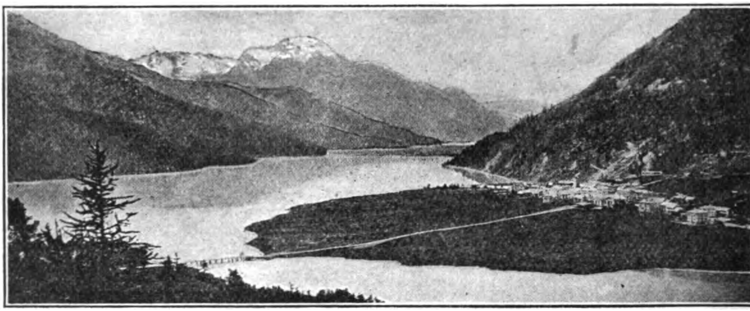


Fig. 119. A delta in a lake. The village is Silva Plana, in the Engadine, Switzerland. (Robin.)

the velocity is checked. In the case of the delta, however, the current is checked more completely, and the debris accumulates (at the outset) below the surface of standing water. Though started below water, deposition on the surface of a delta may build it up to, and even above, the water-level. That part of the delta above water is like a flat alluvial fan. In profile, the delta differs from the alluvial fan in that its edge has a steep slope (compare Figs. 121 and 122).

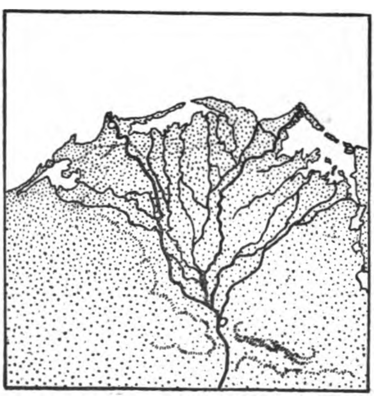
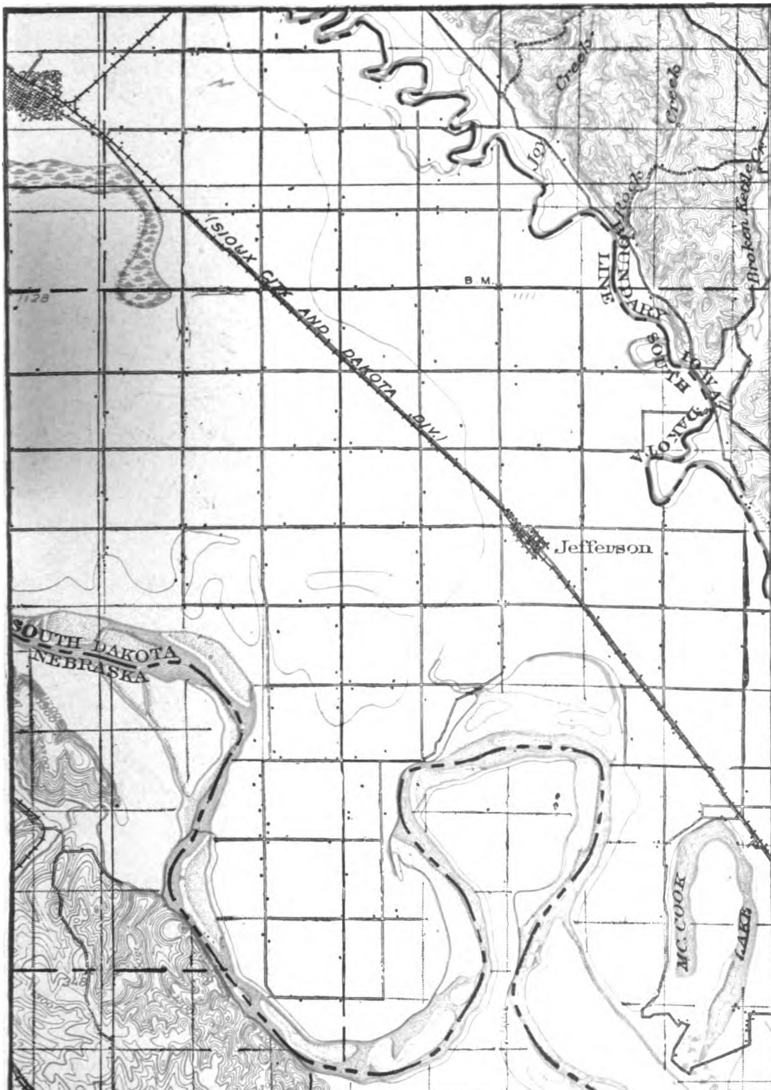


Fig. 120. The delta of the Nile.

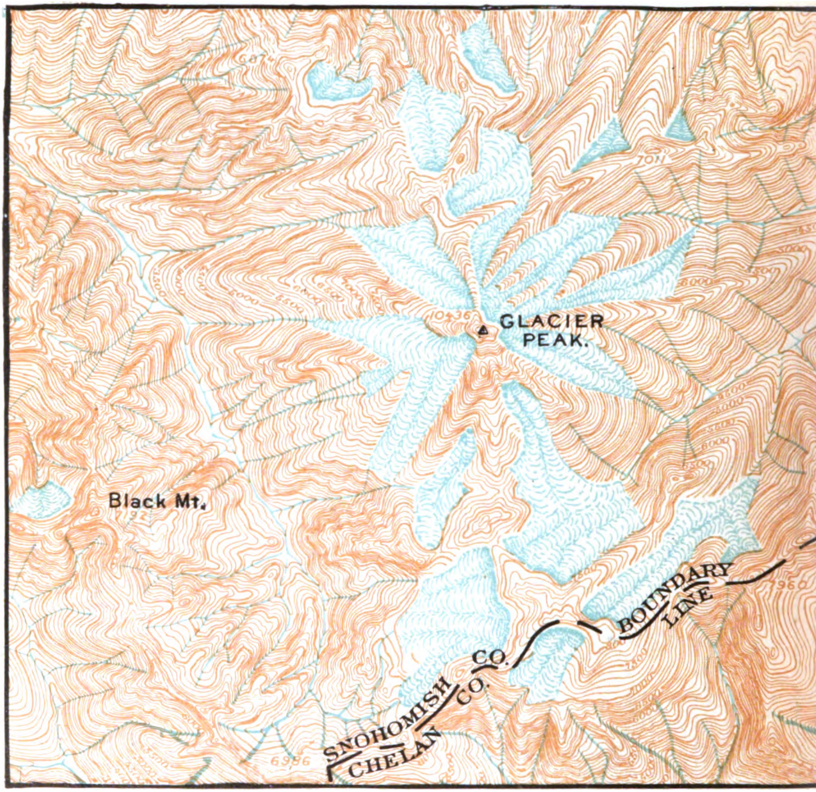
Much land has been made by delta-building. Thus the Colorado River has built a great delta many square miles (above water) in area at the head of the Gulf of California (Fig. 123). The delta has been built quite across the gulf near its upper end, shutting off its head. In the arid climate of the region, this shut-off head has

PLATE XI




Stream flats. The Missouri and Big Sioux Rivers. Scale, about 2 miles per inch. (Elk Point, S. Dak.—Ia.—Neb. Sheet, U. S. Geol. Surv.)

PLATE XII




Glaciers on Glacier Peak, Washington. Scale, about 2 miles per inch. (Glacier Peak Sheet, U. S. Geol. Surv.)

become a nearly dry basin, the lowest part of which is about 300 feet below sea-level. The Skagit River, in Washington, has built its delta out so as to surround what were high islands in Puget Sound, thus joining them to the mainland. The deltas of the Mississippi (Fig. 118), the Nile and the Hoang-Ho Rivers are

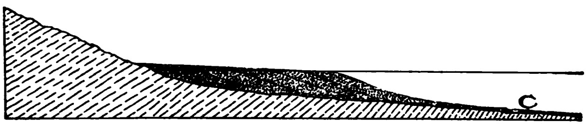



Fig. 121. Diagrammatic profile and section of a delta.

well-known. The united delta of the Ganges and Brahmaputra is also a great one, having an area (above water) of some 50,000 square miles. The Po has built a delta 14 miles beyond the former port of Adria, which gave its name to the Adriatic Sea. The Rhone River (France) has advanced its delta some 15 miles in as many centuries.

The effect of delta-building is to increase the area of the land; but it is to be noted that the processes which lead to delta-building reduce the volume of the land-masses, even though they increase their area.

The outline of some deltas is determined by the surroundings in which they are built. When, for example, a delta is built into a bay, the form of the bay-head determines the shape of the delta.


Fig. 122. Diagrammatic profile and section of an alluvial fan.

The normal form of a delta built on an open coast is somewhat semicircular, though there is in many cases a fringe of *delta fingers* which together have some resemblance to the Greek letter Δ, which gave these terminal deposits of streams their names.

### ALLUVIAL TERRACES

Stream terraces [1] are bench-like flats or narrow plains along the sides of valleys (Fig. 124) and above their bottoms. Most of them are narrow, but some of them have great length.

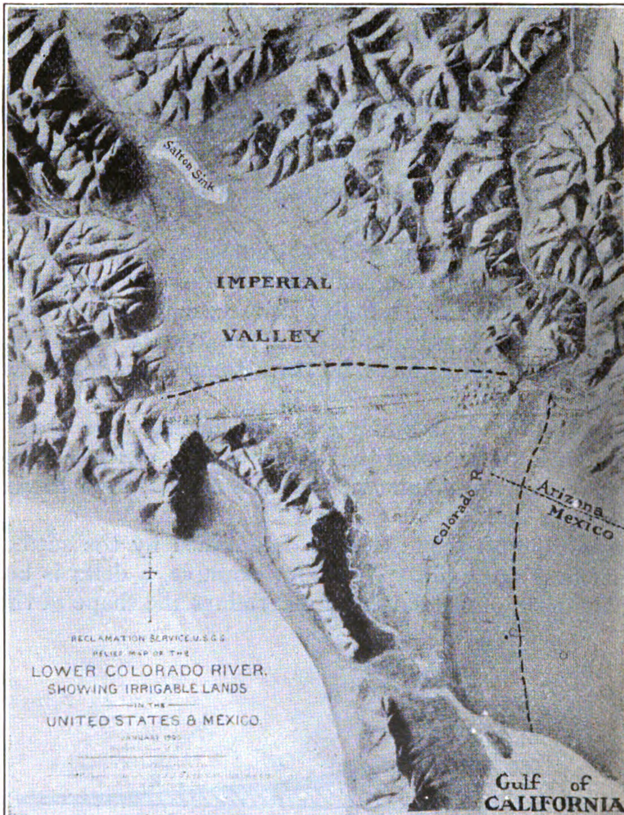



Fig. 123. Relief-map of an area about the head of the Gulf of California, showing the delta of the Colorado River, outlined, in a general way, by dotted lines. The Salton Sink is shown at the north, and the Imperial Valley lies south of the sink. (U. S. Rec. Serv.)

[1] For discussions of terraces see Gilbert's Henry Mountains, p. 126; Davis, Bull. of the Mus. of Comp. Zool. Geol. Series, Vol. V, pp. 282–346; and Dodge, Proc. Boston Soc. of Nat. Hist., Vol. XXVI, pp. 257–273.

Most river terraces are remnants of former flood-plains, below which the streams which made them have cut their channels, but the details of their history are various.

**Normal alluvial terraces.** Alluvial terraces are developed in the normal course of every stream's history, because the first graded plain which a stream develops in its valley is above the level to which the stream can cut at a later time. After the stream has sunk its channel well below the former flood-plain, such parts of the latter as still remain are alluvial terraces. Where a stream's deepened channel is in the middle of its flood-plain, there is a terrace on either

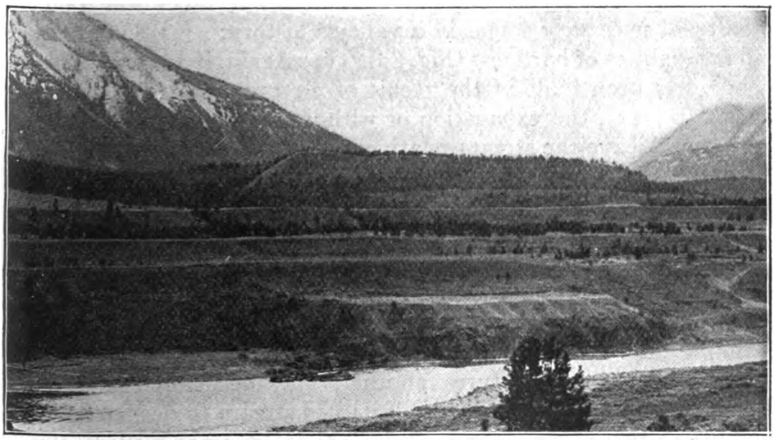


Fig. 124. Terraces on the Fraser River at Lilloet, B. C. (Photo. by Calvin.)

side; but wherever the deepened channel is at one margin of its flood-plain, a terrace remains on the other side only. In some valleys there are several alluvial terraces at different levels. The second terrace (regarding the highest as the first) is developed in the same way as the first, for after the stream has developed a second flood-plain, below the level of the first, it may cut its channel still lower, leaving the remnants of the second flood-plain as terraces. This process may continue until several sets of terraces have been developed. Alluvial terraces developed by the normal activities of a stream are always low, and ordinarily would not be conspicuous. They are not very long-lived, for all processes of subaërial erosion conspire to destroy them. A stream is likely to mean-

der on its second and later flood-plains, as on its first and highest one. Wherever the meanders on its second flood-plain undercut the first terrace, the terrace at that point is subject to destruction, and since the meanders are continually migrating, terraces are continually disappearing. Again, tributary streams cut through the terraces of their mains, and new gullies develop in them, dissecting them still further. At the same time, sheet erosion and other phases of slope wash tend to drive the scarps of the terraces back toward the bluff beyond. By the time a second set of terraces is well developed, no more than meagre remnants of the first may remain.[1]

**Other river terraces.** There are valley terraces which do not represent necessary stages in a valley's history. (1) Some are due to inequalities of hardness (Fig. 80). (2) Again, if an alluvial flood-plain has been built as the result of an excessive supply of sediment (p. 112), the exhaustion or withdrawal of the excessive supply would leave the stream relatively clear, and free to erode where it had been depositing. It would forthwith set to work to carry away the material which it had temporarily unloaded on the plain. The valley plains built up in many valleys in the northern part of our continent during the glacial period, when drainage from the ice flowed through them, have been partially destroyed since and their remnants are terraces. (3) A notable increase in the volume of a stream, without corresponding increase in load, as when one stream captures another, may occasion the development of terraces by allowing the enlarged stream to deepen its channel. (4) The uplift of a region in which there are well developed river flats, would rejuvenate the streams, and parts of their old flood-plains would be left as terraces. Other occasional causes which need not be mentioned here, develop terraces from flood plains.

In conclusion, it is to be emphasized that many river terraces, mostly very low, are normal features of valley development, coming into existence at definite stages in a valley's history. They are generally composed, in large part, of river alluvium. Others result from more or less accidental causes, working singly or in conjunction, and to this class belong many of the more conspicuous terraces developed from flood-plains.

**Laboratory work.** See excercises III-IX, in laboratory manual *Interpretation of Topographic Maps;* also Professional Paper 60. U. S. G. S. Pls. XXIII-LXXXIX.

[1] For a fuller statement of the manner in which alluvial terraces are developed, see the authors' Geologic Processes.

## CHAPTER V

### THE WORK OF SNOW AND ICE

**Ice beneath the surface.** The wedge-work of ice in the crevices of rock has already been mentioned (p. 25). When the great areas where water freezes during some part of the year are considered, it is clear that the aggregate effect of its freezing in the pores and crevices of rock must be great in long periods of time. Even the freezing of water in the soil is not without effect. This is shown by the disturbance of the walls of buildings if their foundations are not below the depth of freezing, and by the working up of stones and bowlders through the soil of the fields, as freezing and thawing succeed each other. Frozen water in the soil makes it solid, and temporarily retards or prevents surface erosion.

**Ice on lakes and ponds.** Since fresh water is densest at 39° Fahr., ice does not commonly form on the surface of a lake until the temperature from top to bottom is reduced to this point. Cooled below 39°, the surface water fails to sink, and cooled to 32°, it freezes. If the lake is small and shallow, it will freeze over completely where the temperature is notably below 32° for any considerable period of time. It is under these circumstances that lake ice becomes most effective.

Let us suppose a lake in temperate latitudes, where the range of winter temperature is considerable, to be frozen over when the temperature is 25° Fahr. If now the temperature is lowered to −10°, and such a temperature is not uncommon in the northern part of the United States, the ice contracts. In contracting, it either pulls away from the shores, or cracks. If the former, the water from which the ice is withdrawn quickly freezes; if the latter, water rises in the cracks and freezes there. In either cases, the ice-cover of the lake is again complete. If the temperature now rises to 25° the ice expands, and the solid cover becomes too large for the lake, and must either crowd up on the shores, or arch up (wrinkle) elsewhere.

If the water near the shore is very shallow, the ice freezes to the

sand, gravel, and bowlders at the bottom. If the land at the shore is very low, the ice in expanding may shove up over it, carrying the debris frozen in its bottom, and it may push loose gravel, sand, etc., in front of its edge. Where bowlders are frozen to the bottom of the ice, the shoreward thrust as the ice expands shifts them toward the shore, and they may be shoved up a little above the normal water-level. The concentration of bowlders at the shore-line, year

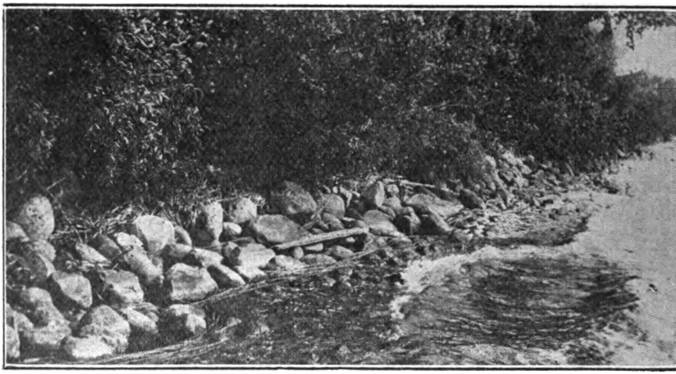


Fig. 125. Shore of Wall Lake, Iowa. (Photo. by Calvin.)

by year, gives rise to the "walled" lakes (Fig. 125), which are not uncommon in the northern part of the United States. The "wall" does not commonly extend entirely around a lake.

If a lake is bordered by a low marsh, the ice and frozen earth of the latter are really continuous with the ice of the lake, and the push of the latter may arch up the former into distinct ridges (anticlines), the frozen part only being involved in the folds (Fig. 126). A succession of colder and less cold periods may give rise to a succession of such anticlines.[1] If the shore is steep, the crowding of the ice against a low cliff of yielding material, such as clay, disturbs all above the shore-line (Fig. 127). Where the cliff is sufficiently resistant, it withstands the push of the ice, and the ice itself is warped and broken.

**On rivers.** Rivers also freeze over in cold climates, and when the ice breaks up in the spring, the stones and bowlders to which it was frozen in the banks may be floated miles down the river. At

[1] Buckley, Wis. Acad. of Sci., Vol. XIII, Pt. I, 1900. A study of ice ramparts formed about the shores of Lake Mendota, Wis., in 1898–99.

Fig. 126. Shove of shore ice where the shore was marshy. The ice of the frozen marsh is pushed up into ridges. (Buckley, Wis. Geol. Surv.)

Montreal stone buildings 30 to 50 feet square, projecting so as to have river ice form about them, have been moved by the ice of the St. Lawrence.

When the river ice breaks up, masses of it are carried down-

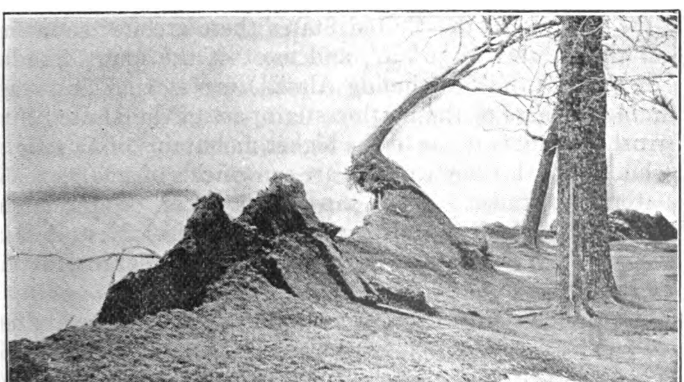


Fig. 127. The shove of ice on the shore of Lake Mendota, Wis. (Photo. by Buckley.)

stream, and in some cases accumulate in vast "jams" behind obstructions in the river. Where a jam forms above a bridge, the bridge may be swept away. Some jams occasion disastrous floods above their sites, and when they break, the waters accumulated above may sweep down the valleys with destructive violence. Poleward-flowing rivers are especially subject to such floods. The snows of their upper basins melt while the lower parts of the streams are still frozen over. The free discharge of the upper waters is thus prevented for a time, and freshets follow.

**On the sea.** In high latitudes, ice is formed along the seashore. Unlike fresh water, sea-water condenses until it freezes, at a temperature of 26° to 28° Fahr., the variation being due to the amount of salt in the water. In polar regions the sea ice attains a depth of eight or ten feet at least. Floating ice of much greater thickness is sometimes seen, but it is doubtful if it represents ice formed by the freezing of undisturbed sea-water. The geologic importance of ice formed on the sea is slight.

**Snow-fields.** Over the larger part of the land, the snow of winter does not endure through the summer, and when it melts, the water follows the same course as rain; but in cold regions where the fall of snow is heavy, some of it remains unmelted from year to year, and constitutes perennial snow-fields. High mountains and the lands of high latitudes are the common habitats of snow-fields. In North America there are numerous small snow-fields in the western mountains, from Mexico to Alaska, their number and size increasing to the north. In the United States there are few snow-fields south of the parallel of 36° 30′, and most of the many hundreds north of that latitude (excluding Alaska) are small. Snow-fields comparable to those of the northwestern part of the United States and British Columbia occur in the higher mountains of Europe and Asia, while in South America there are snow-fields of small size even in equatorial latitudes. Small snow-fields occur on the highest peaks of tropical Africa, and in the mountains of New Zealand. For reasons which will appear later, much of every large snow-field is really ice.

Besides these fields of snow in mountain regions, there are fields of much greater extent in polar regions. The greater part of Greenland is covered with a single field of ice and snow, the size of which is estimated at 300,000 to 400,000 square miles (Fig. 128),—an area 400 to 600 times as large as the snow-and-ice-covered area of Swit-

zerland. Numerous islands to the west of North Greenland are also partly covered with snow. In Antarctica there is a still larger field, the largest of the earth. Its area is not known, but its extent is at least 6 or 8 times as great as that of Greenland.

The only condition necessary for a snow-field is an excess of snow-fall over snow-waste. The lower edge of a snow-field, the *snow-line*, is dependent chiefly on temperature and snow-fall. It does not depart much from the summer isotherm of 32°, though where the snow-fall is light, it may be above this isotherm. That the snow-line is not a function of temperature only, is shown by its position in various places. Thus in the equatorial portion of the Andes, the snow-line has an altitude of about 16,000 feet on the east side of the mountains, where the precipitation is heavier, and of about 18,500 feet on the west side, where it is lighter. For the same reason the snow-line in the Himalayas is lower on the south side than on the north. Though temperature and snow-fall are the most important factors controlling the position of the snow-line, both humidity and movements of air are of some importance, since both affect the rate of evaporation of snow and ice.

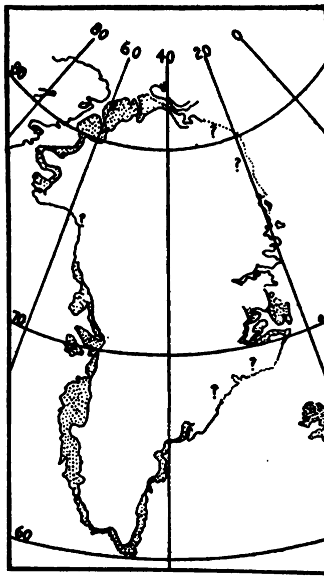


Fig. 128. Map showing the ice-cap of Greenland. Only the borders (shaded parts) of the island are free from ice.

**Change of snow to ice.** Snow does not lie on the surface long before it undergoes obvious change. The light flakes are transformed into granules, and the snow becomes "coarse-grained." The granular character, so pronounced in the last banks of snow in the spring, is even more distinct in perennial snow-fields. This granular snow is called *névé*. Where the thickness of the snow is great, the névé becomes compact below, and grades into porous ice. Ice is found in some snow-fields at no great depth from the surface.

**Structure of the ice.** The ice of a snow-field is in some sense *stratified*. It is made up of successive falls of snow which tend to

retain their individuality. Thus the snow of one season may have been considerably changed before the next season. Again, the surface of the snow-field at the end of the melting season is generally soiled by a little earthy matter, some of which was blown up on the surface during the melting season, and some of which was concentrated at the surface by the melting of the snow in which it was originally imbedded. In many places this earthy matter is sufficient to define snows of successive years, giving the ice a somewhat stratified appearance.

In addition to its stratification, the ice of the deeper portions may take on a stratiform structure which may be called *foliation*, to distinguish it from the stratification which arises from deposition. Foliation appears to be akin to slaty or schistose cleavage, and to result largely from the shearing of one part of ice over another, as it moves forward.

**Texture.** Ice formed from snow is composed of interlocking crystals. The crystalline character is assumed by the snow-flakes when they form, and the subsequent changes which the snow undergoes seem to modify the original crystals by building up some and destroying others. By the time the snow is converted into névé, the granules have become coarse, and wherever the ice derived from the névé has been examined, the granular crystalline texture is present. The individual crystals in the ice are usually larger than those of the névé, and more closely grown together. In compact ice, the crystals are so intimately interlocked that they are not seen readily by the eye; but when the ice has been honeycombed by partial melting, the granules become partially separated and may be seen easily. It is therefore legitimate to assume that a granular crystalline condition persists throughout all stages of the history of ice formed from snow.

**Inauguration of movement.** When the ice beneath a snow-field becomes very deep, motion is developed. The exact nature of the motion has not been demonstrated to the satisfaction of all who have studied the problem, though much is known about it. Brittle and resistant as ice seems, it may, under proper conditions, be made to exhibit some of the characteristics of a plastic substance. A piece of ice may be made to change its form, and may even be moulded into almost any desired shape if subjected to sufficient pressure, applied steadily through long intervals of time.[1] These changes may be brought about without visible fracture, and have been

thought to point to a viscous condition of the ice. There is much reason, however, to question this interpretation. Whatever the real nature of the movement, its aggregate result in a field of ice is comparable, in a superficial way at least, to that which would occur if the ice were capable of moving like a viscous liquid, the motion taking place with extreme slowness. This slow motion of ice in an ice-field is glacier motion, and ice thus moving is *glacier ice.* The *cause* of movement is gravity, which tends to bring the ice to lower levels, just as it tends to bring water, in similar positions, to lower levels.

### GLACIERS

**Types.** The different shapes of glaciers have given rise to different names. If the surface on which the ice-sheet develops is plane, the ice will move outward in all directions, and ice spreading in all directions from a center is an ice-cap. The glacier covering the larger part of Greenland (Fig. 128) is a good example. The glaciers on some of the flat-topped peninsular promontories of the same island are examples of small ice-caps (Fig. 129). If ice-caps cover a large part of a continent, as some of those of the past have done, they are called *continental glaciers.*

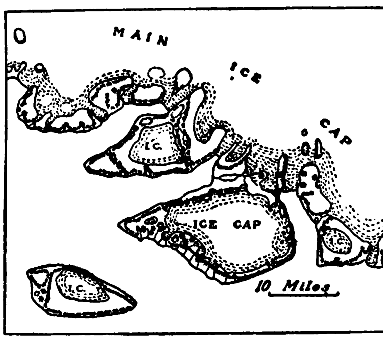



Fig. 129. Ice-caps of small size. The figure also shows some valley glaciers extending out from the main ice-sheet and from the local ice-caps. A portion of the North Greenland coast, north of Inglefield Gulf. Lat. about 78°.

Where ice-caps lie on plateaus whose borders are dissected by valleys, tongues of ice from the ice-cap may extend down the valleys. They constitute one type of *valley glacier.* A second and more familiar type of valley glacier occupies mountain valleys, and is the offspring of mountain snow-fields. The former type, confined chiefly to high latitudes, are *polar* or *high-latitude* glaciers (Fig. 130); the latter are *alpine* glaciers (Figs. 131, 132). The distinctive feature of high-latitude glaciers is their steep slopes at sides and ends.

[1] For an account of experiments illustrating the mobility of ice see Aitkin, Am. Jour. Sci., Vols. V, 1873, p. 305, and XXXIV, 1887, p. 149, and Nature, Vol. XXXIX, p. 203.

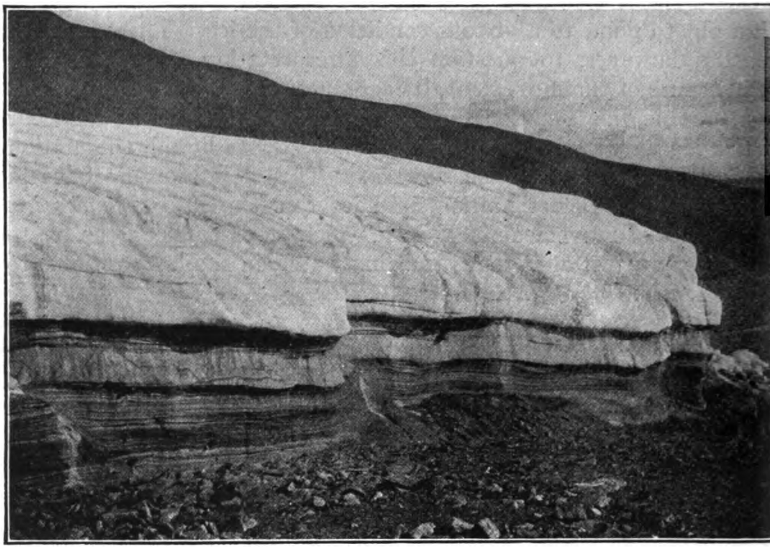


Fig. 130. End of Bryant glacier, a high-latitude glacier of North Greenland.

Fig. 131. The Rhone glacier. (Photo. by Reid.)

Fig. 132. The medial moraine of the Roseg Glacier, Switzerland.

When a valley glacier descends through its valley to a plain beyond, its end spreads. If the deploying ends of adjacent glaciers merge, the resulting body of ice constitutes a *piedmont glacier* (Fig. 133). Piedmont glaciers are confined to high latitudes. In some

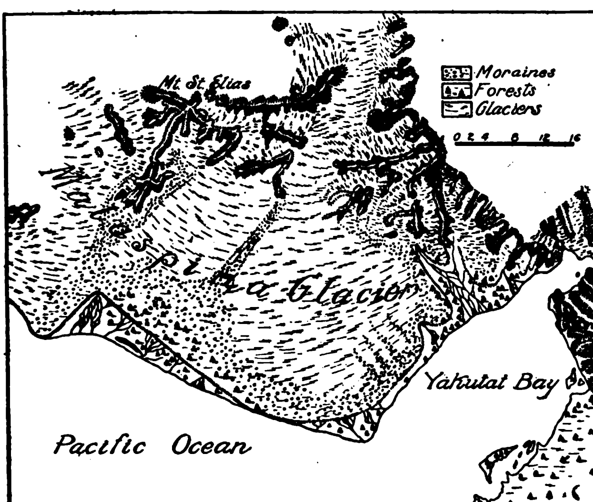



Fig. 133. Malaspina Glacier, a piedmont glacier in Alaska. (After Russell.)

cases the snow-field that gives rise to a glacier is restricted to a relatively small depression in the side of a mountain, or in the escarpment of a plateau. In such cases the snow-field and glacier are hardly distinguishable, and the latter descends but little below the snow-line. Such a glacier, nestled in the face of a cliff, has been called a *cliff glacier*[1] (Fig. 134). Cliff glaciers may be as wide as

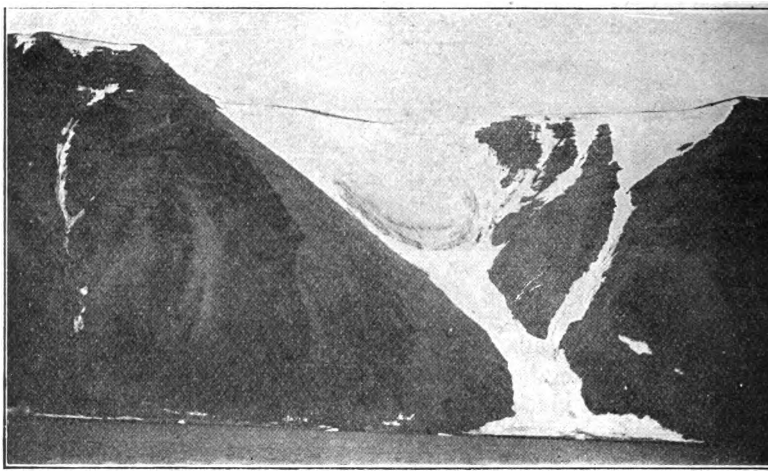


Fig. 134. A cliff glacier, coast of North Greenland. The height of the cliff is perhaps 2,000 feet. The water in the foreground is the sea.

long, and are always small. Between them and valley glaciers there are all gradations (Fig. 135). Occasionally the end of a valley glacier, or the edge of an ice-sheet, reaches a precipitous cliff, and the end or edge of the ice breaks off and accumulates like talus below. The fragments of ice may then become a coherent mass by regelation, and the whole may resume motion. Such a glacier is called a *reconstructed glacier*. The precipitous cliffs of the Greenland coast furnish illustrations.

Of the foregoing types of glaciers, ice-caps far exceed all others in both size and importance, while valley glaciers outrank the remaining types; but since valley glaciers are the most familiar, the general phenomena of glaciers will be discussed with primary reference to them.

[1] Jour. of Geol., Vol. III, p. 888.

Fig. 135. Glaciers intermediate in type between cliff glaciers and valley glaciers. Cascade Mountains, Wash. (Willis, U. S. Geol. Surv.)

### *General Phenomena of Glaciers*[1]

**Dimensions.** Some valley glaciers occupy only the upper parts of mountain valleys, others extend through them, and push out on the plain beyond. In length they range from a fraction of a mile to many miles. Their thickness is usually measured by scores or hundreds of feet rather than by denominations of a larger order, but the variation is great. The minimum thickness is that which is necessary to cause movement, and this varies with the slope, the temperature, and other conditions. There is also much variation in the thickness in different parts of the same glacier. As a rule, it is thinnest in its terminal portion, and thickest at some point between its terminus and its source. Cliff and reconstructed glaciers

[1] The following list includes some of the more available articles and treatises on existing glaciers; others are referred to in the following pages.

*Alaskan glaciers:* Reid, (1) Nat. Geog. Mag., Vol. IV, pp. 19–55; (2) Sixteenth Ann. Rept., U. S. Geol. Surv., Part I, pp. 421–461. Russell, (1) Nat. Geog. Mag., Vol. III, pp. 176–188; (2) Jour. of Geol., Vol. I, pp. 219–245.

*Glaciers in the United States:* (1) Russell, Eighteenth Ann. Rept., U. S. Geol. Surv., Part II, pp. 379–409; (2) Glaciers of North America.

*Greenland glaciers:* Chamberlin, Jour. of Geol., Vol. II, pp. 768–788; Vol. III, pp. 61–69, 198–218, 469–480, 565–582, 668–681, and 833–843; Vol. IV, pp. 582–592. Salisbury, Jour. of Geol., Vol. IV, pp. 769–810.

are comparable in size to the smaller valley glaciers. An ice-cap is thickest, theoretically, at its center, and thins away to its borders; but its actual thickness is influenced by the topography of the surface beneath it. The Greenland ice-cap rises about 9,000 feet above the sea toward its southern end, and it probably rises higher in the unexplored center of the broader part of the island. The height of the rock surface beneath the ice is unknown, but it is unlikely that it averages half this amount, and hence the ice is probably very thick at its center.

**Limits.** The ice of a glacier is always moving forward, but the *end* of a glacier may be retreating, advancing, or remaining stationary, according as waste exceeds, falls short of, or equals forward movement. The position of the lower end of a glacier is therefore determined by the ratio of movement to waste. Its upper end is generally ill-defined. In a superficial sense, it is where the ice emerges from the snow-field; but the lower limit of the snow-field is ill-defined, and in any case is not the true upper limit of the glacier. The snow-field is really an ice-field covered with snow, and there is movement from it to the tongue of ice in the valley. The ice so moving is, in reality, a part of the glacier. The lower end of a glacier is usually free from snow and névé in summer, but its upper end is covered with névé or snow, and finally merges into the snow-field without ceasing to be a glacier. The term glacier is, however, commonly used to mean merely the more solid portion outside (below) the snow-field.

**Movement.** The advance of a glacier is too slow, as a rule, to be seen from day to day, but is detected in other ways. If its end advances, it overrides or overturns objects which were in front of it, or it moves out over ground previously unoccupied. But even when the end of a glacier is not advancing, movement of the ice may be established by means of stakes or other marks on its surface. If the position of these marks relative to fixed points on the sides of the valley is noted, they are found, after a time, to have moved down the valley.

Rows of stakes or lines of stones set across a glacier in its upper, middle and lower portions have revealed many facts concerning the movement of the ice. Generally speaking, the central part moves faster than the sides, and the top faster than the bottom. In Switzerland the determined rates of movement range from one or two inches to four feet or more per day. Some of the larger glaciers

in other regions move more rapidly, but it does not follow that large glaciers always move faster than small ones. The Muir glacier of Alaska has been found to move some seven feet per day,[1] and some of the glaciers of Greenland move, in the summer time, 50 or 60 feet per day; but these rates have been observed only where the ice of a large inland area crowds down into a comparatively narrow fiord, and debouches into the sea, and there only in the summer. In the case of the glacier with the highest recorded summer rate of movement (100 feet per day), the advance was only 34 feet a day in April. The average movement of the border of the inland ice of Greenland is very small, probably less than a foot a week.

**Conditions affecting rate of movement.** The rate of glacier movement depends on (1) the depth of the moving ice, (2) the slope of the surface over which it moves, (3) the slope of the upper surface of the ice, (4) the topography of its bed, (5) the temperature of the ice, and (6) the amount of water it contains. Great thickness, steep slopes, smoothness of bed, a high (for ice) temperature, and abundance of water, favor rapid movement. Since some of these conditions, notably temperature and amount of water, vary with the season, the rate of movement of a glacier varies during the year. Other conditions vary through longer periods of time, and cause corresponding variations in the rate of movement.

A sloping upper surface is essential to glacier motion, and the motion is down-slope. There are short stretches where this is not the case; indeed there are places where the upper surface declines away from the direction of motion, as where the ice pushes up over a swell in its bed; but such cases are local exceptions and do not militate against the general truth of the statement that the upper surface of a glacier declines in the direction of motion. A declining *lower* surface is less necessary. In the case of a valley glacier, the bed does, as a rule, decline in the direction of motion; but the deep basins in rock which many such glaciers leave behind them when they retreat, show that the bottom of a valley glacier does not slope downward at all points. In the great continental glaciers of recent geologic times, the ice moved up slopes for scores, and even hundreds of miles; but in all such cases, the *prevailing slope* of the upper surface was *down* in the direction of movement.

**Fluctuations of glaciers.** The lower ends of glaciers advance

[1] Reid. Natl. Geog. Mag., Vol. IV, p. 44.

and retreat at intervals[1], and the periods of advance follow a succession of years when the snowfall was heavy and the temperature low, while the periods of retreat follow years when the snowfall was light and the temperature above normal. The periods of advance and retreat lag behind the periods of heavy and light snowfall, respectively, by some years, and a long glacier responds less promptly than a short one.

Fig. 136. Aletsch Glacier, Switzerland.

**Likenesses and unlikenesses of glaciers and rivers.** Slope, roughness of bed, and volume affect the movement of glaciers somewhat as they affect the movement of rivers. The temperature of water, on the other hand, has little effect on its flow, so long as it remains unfrozen; but the effect of temperature on the motion of ice is important. In many cases, indeed, the temperaature, together with the water that is incidental to it, seems to be the chief factor in determining its rate of movement. Its effects will be discussed later.

From Fig. 136 it will be seen that a valley glacier is an elongate body of ice, following the curves of the valley in stream-like fashion. It has its origin in the snows collected on the mountain heights, and it works its way down the valley in a manner which, in the aggregate, is similar to the movement of a stiff liquid. The likeness to a river extends to many details. Not only does the center move faster than the sides, and the upper part faster than the bottom, as in the case of streams, but the movement is more rapid in the narrow parts of the valley and slower in the broader. These

[1] Reid. Variations of Glaciers. Occasional articles in Journal of Geology, Vol. III and later volumes.

and other likenesses, some of which are apparent rather than real, gave rise to the view that glacier ice moves like a stiff, viscous liquid.

But while the points of likeness between glaciers and rivers are several, their differences are numerous and significant. The most obvious difference is the fact that the glacier is fractured readily, as the numerous gaping crevasses on many glaciers show. Some of the crevasses are longitudinal, some are transverse, and some are oblique. In the case of arctic glaciers, longitudinal crev-

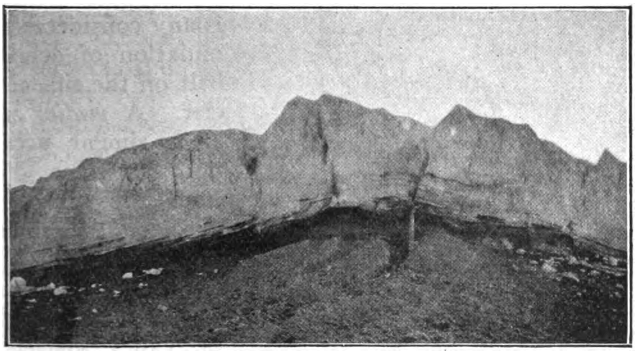


Fig. 137. Crevassed glacier, the cracking due to change in grade of bed. North Greenland.

assing is especially conspicuous. *Crevasses* appear to be developed wherever there is appreciable tension, and the causes of tension are many. An obvious cause is an abrupt increase of gradient in the bed (Fig. 137). If the change of gradient is considerable, an ice-fall or cascade results, and the ice may be greatly riven. Some of the transverse crevasses at the margins appear to be the result of tension developed on curves. Oblique crevasses on the surface near the sides are commonly ascribed to the tension between the faster-moving center and the slower-moving margins, and in like manner cracks that rise obliquely from the bottom are attributed to the tension between the faster-moving parts above and the slower-moving parts below. All crevasses indicate strains. Liquids, whose pressures are equal in all directions, show nothing analogous to crevassing. Longitudinal crevasses may affect both the narrow part of a glacier and its deploying end, and are the result of tension developed by movement within the ice itself, to which,

again, rivers offer no analogy. All cracks show that the glacier is a very brittle body, incapable of resisting even very moderate strains brought to bear upon it very slowly. In its behavior under tension, therefore, a glacier is notably unlike a river.

**Surface moraines.** The surfaces of many glaciers are affected by rock debris, some of which is disposed in the form of belts or *moraines* (Fig. 138). The surface moraines may be *lateral*, *medial*, or *terminal*. A *lateral moraine* is any considerable accumulation of debris in a belt on the side of a glacier. A *medial moraine* is a similar accumulation at some distance from the margins, but not necessarily in or even near the middle. There may be several medial moraines on one glacier. In valley glaciers, the *surface terminal* moraine may connect two lateral moraines, making a loop roughly concentric with the end of the glacier. Besides the surface moraines, there may be scattered bowlders and bits of rock of various sizes on the ice, and, in addition to the coarse material, there is in many cases some dust which has been blown upon the ice.

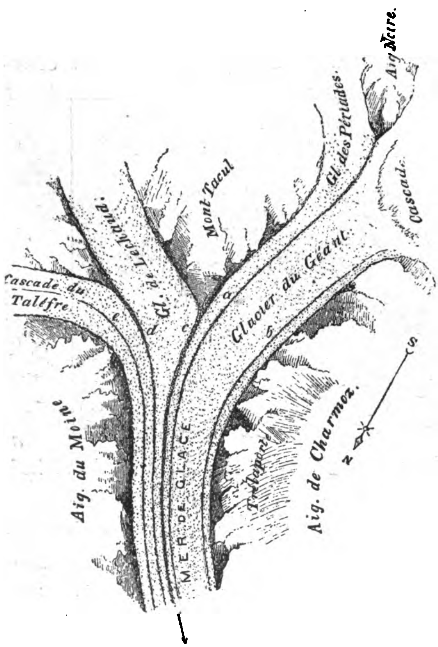



Fig. 138. Lateral and medial moraines, the latter formed by the union of glaciers.

**Relief due to surface debris.** The debris on the ice affects its topography by influencing the melting of the ice beneath and about it. Rock debris absorbs heat more readily than the ice. A thin piece of stone lying on the ice is warmed through by the sun's rays, and, melting the ice beneath, sinks, just as a piece of black cloth would. Though a good absorber of heat, rock is a poor conductor, and so the lower surface of a thick mass of stone is not warmed

notably, and the ice beneath, being protected from the sun, is melted less rapidly than that around it. The result is that the bowlder presently stands on a protuberance of ice (Fig. 139). When its pedestal becomes high, the oblique rays of the sun and the warm air surrounding it cause it to waste away, and the capping bowlder falls.

The same principles apply to moraines. A surface moraine protects the ice beneath from melting, and causes the development of a ridge of ice beneath itself. As the ice on either side is lowered by ablation, the moraine matter tends to slide down on either hand. So far does this spreading go, that in some cases the lower end of a glacier is completely covered with debris which has spread from medial and lateral moraines.

Fig. 139. A glacial table due to the protection of the ice beneath the flat stone from the rays of the sun. Talèfre Glacier.

**Debris below the surface.** Debris carried by a glacier is not restricted to its upper surface. Debris near the bottom is in some cases so abundant, especially near the ends and edges of the ice, that it is difficult to locate the bottom of the glacier; for between the moving ice which is full of debris, and the stationary debris which is full of ice, there seems to be complete gradation. The debris in the lower part of arctic glaciers, and to some extent of others, is in many cases disposed in thin sheets between layers of clean ice. Debris also occurs to some extent in the ice far above its base, in some places in sheets and in

some places in bunches. These various relations are illustrated by Figs. 140 and 141.

**Drainage.** Some of the water produced by surface melting forms little streams on the ice. Sooner or later they plunge into crevasses or over the sides and ends of the glacier. In the former case, they may melt or wear out well-like passages (*moulins*) in the

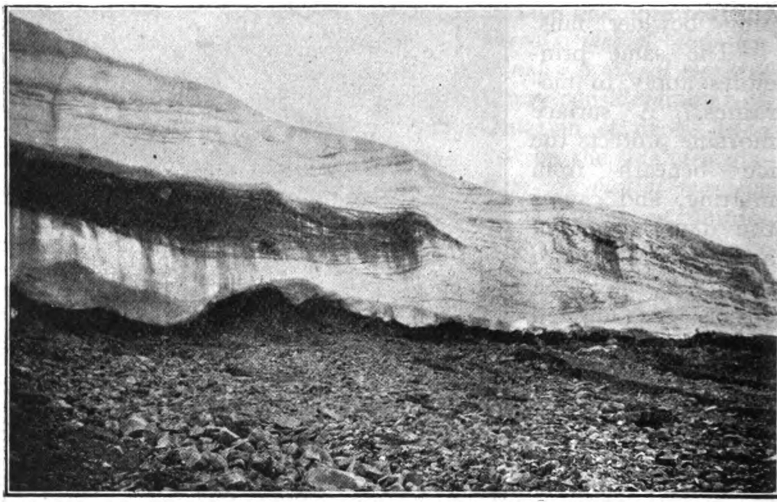


Fig. 140. Side view of end of glacier. Southeast side of McCormick Bay, North Greenland. Shows foliated structure of ice as well as position of debris.

ice, and holes or "wells" in the rock beneath. Much of the surface water sinks into the ice without forming streams. The depth to which water penetrates is undetermined by observation, but it doubtless goes down to the zone of constant temperature in all cases, and still lower where there are crevasses, and where the temperature is not below freezing.

Once within the glacier, the course of the water is variable. Exceptionally it follows definite englacial channels, as shown by the springs and streams which issue from some glaciers above their bottoms. More commonly it descends or moves forward through the irregular openings which the accidents of motion have made. If it reaches a level where the temperature is below 32° it freezes. Otherwise it remains in cavities or descends to the bottom. The

water produced by melting within the glacier probably follows a similar course. So far as these waters descend to the bottom, they join those produced by basal melting, and issue from the glacier with them. In some alpine glaciers, the waters beneath the ice unite in a common stream in the axis of the valley, and hollow out a tunnel in the bottom of the ice. The Rhone River is already a considerable stream where it issues from beneath the glacier. In high latitudes, subglacial tunnels are not common, and the drainage is in streams along the sides of the glaciers, or through the debris beneath and about them.

Fig. 141. A part of the vertical side of a North Greenland glacier. The vertical or even overhanging faces are in some cases more than 100 feet high.

At the end of the glacier, all waters, whether they have been superglacial, englacial, or subglacial, unite to bear away the silt, sand, gravel, and even small bowlders set free from the ice, and to spread them in belts along the border of the ice, or in trains stretching down the valleys below, forming *glacio-fluvial* deposits.

The structure and the motion of glacier ice have been the subject of much discussion. Though universal agreement concerning them has not been reached, a brief outline of one of the current views is added. Mention also is made of other views, some of which are still held by various geologists.

### THE STRUCTURE OF GLACIER ICE

The key to the structure and motion of glacier ice is based on the view that a glacier is a mass of crystalline rock of the purest and simplest type known. It is made of a single simple mineral, ice, which is always crystalline. It differs from other rock chiefly in that its one mineral is liquefied at a low temperature.

*The development of ice from snow.* The fundamental conception of a glacier is best developed by tracing the growth of its constituent crystals. When

water solidifies from the vapor of the atmosphere, it takes the form of separate crystals (Fig. 142). The flakes are rarely perfect, but they are always crystals. Snow crystals may continue to grow so long as they are in the atmosphere; or if the air is warm or dry they shrink, from melting or evaporation. When they reach the ground, the processes of growth and shrinking continue, and the crystals increase or decrease according to circumstances.

A glacier is a colossal aggregation of crystals grown from snowflakes to granules of greater size and more compact form. The microscopic study of snowflakes shows how they change from flakes to granules. The slender points and angles of new-fallen flakes melt and evaporate more than the central portions. The water (and doubtless the water vapor) thus formed gathers about the centers of the flakes and, if the temperature is right, freezes there.

These are first steps toward the pronounced granulation of snow which has lain long on the ground. Measured from day to day, the larger granules beneath the surface of coarse-grained snow are found to be growing. When the temperature of the atmosphere is above the melting-point, the growth is faster than when the air is colder, but there is *an increase in the average size of the granules, and a decrease in their number, under all conditions of temperature.* Part of the increase of the larger granules appears to be at the expense of the smaller ones; part doubtless comes from the moisture of the atmosphere which penetrates the snow and condenses there, and part from the descent of water due to surface melting.

Deep beneath the surface of a large body of snow, the larger part of the growth of the large granules is probably at the expense of the small ones. To understand how this takes place, it should be noted that the free surface of every granule is constantly throwing off particles of water-vapor (i. e., evaporating); that the rate of evaporation increases with the sharpness of the curve of the surface, and that the smaller the particles, the sharper the curve; that the surface of a granule is liable to receive and retain molecules evaporated from other granules, and that, other things being equal, the retention of particles is most common on surfaces of least curvature. It follows that the larger granules of less curvature will lose less and gain more, on the average, than the smaller granules. The result is that the larger granules grow at the expense of the smaller.

Another factor affecting the growth of granules is *pressure and tension.* The granules are compressed at their points of contact, and under tension elsewhere. Tension increases the tendency to evaporation, and the capillary spaces adjacent to the points of contact probably favor condensation. Pressure reduces the melting-point, while tension raises it. Though the effect of this is slight, it is to be correlated with the much more important fact that *compression produces heat* which may bring the temperature of the ice to the melting temperature at some points, while tension may reduce it to or below freezing temperature at adjacent points. There is therefore a tendency for the ice *to melt at points of contact and compression, and for the water so produced to refreeze at adjacent points where the surfaces of granules are under tension.* This process becomes effective beneath a considerable body of snow, and here the granules gradually lose the spheroidal form assumed in the early stages of granulation, and become irregular polyhedrons, interlocked into a mass of more or less solid ice.

Whether these processes furnish an adequate explanation of the changes or not, all gradations may be observed from snowflakes to granular névé, and thence to the granules of glacier ice, ranging in size up to that of walnuts, and even

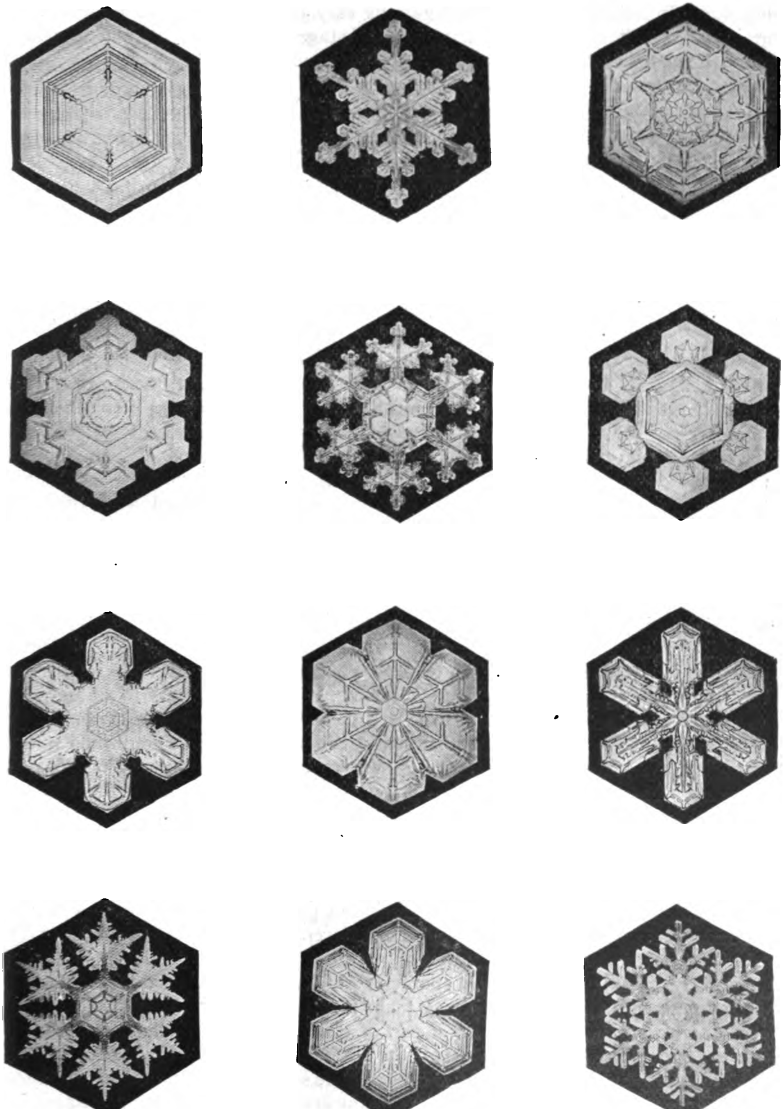


Fig. 142. Photographs of snowflakes, enlarged. (Bentley.)

beyond. In coherence, these aggregations vary from the névé stage, where the grains are small and spheroidal, to the ice stage, where the cohesion is strong through the interlocking growths of the large granules.

### MOTION OF GLACIER ICE[1]

*Rotation and sliding of granules.* There seems to be no escape from the conclusion that the primal cause of glacier motion is one which may operate even under the relatively low temperatures, the relatively dry conditions, and the relatively granular textures at the heads of glaciers. These considerations lead to the view that movement there takes place by the movements of the grains upon one another. While they are in the spheroidal form, as in the névé, this would not seem to be difficult. They may rotate and slide over each other as the weight of the névé increases, and the motion between the granules might be comparable to that between shot in great quantities in similar positions. The amount of motion required of an individual granule is surprisingly small. In order to account for a movement of three feet per day in a glacier six miles long, the mean motion of the average granule relative to its neighbor would be roundly, $\frac{1}{10000}$ of its own diameter per day; in other words, it *should change its relations to its neighbors* to the extent of its diameter once in about thirty years. A change of such slowness under the conditions of granular alteration can scarcely be thought improbable.

*Melting and freezing.* After the granules become interlocked, as in the body of the glacier below the névé field, rotation and sliding must be more difficult. Then, if not earlier, the movement between granules is supposed to be effected chiefly by the temporary passage of minute portions of the granules into the fluid form at points of greatest compression, the transfer of the water thus produced to adjoining points, and its resolidification. The points of greatest compression are obviously those whose yielding most promotes motion, and the successive yielding of points which come in succession to oppose motion most (and thus to receive the greatest stresses), permits continuous motion. It is only necessary to assume that the gravity of the accumulated mass is sufficient to produce a little temporary liquefaction at the points of greatest stress, the result being accomplished not so much by the lowering of the melting-point as by the development of heat by pressure. This is believed to be the largest single element in glacier motion.

This conception of glacial movement involves the *momentary liquefaction of minute portions of the ice*, while the mass as a whole remains rigid, as its crystalline nature requires. Instead of assigning a slow viscous fluidity like that of asphalt to the *whole* mass, which seems inconsistent with its crystalline character, it assigns a free fluidity, momentarily, to a succession of particles that form only a minute fraction of the whole at any instant. This conception is consistent with the retention of the granular condition of the ice, with its rigidity and brittleness, and with its strictly crystalline character, a character which a viscous liquid does not possess, however much its high viscosity may make it resemble a rigid body.

*Accumulated motion in terminal part of glacier.* However slight the relative motion of one granule on its neighbor, the granules in any part of a glacier partake in the accumulated motion of all parts nearer the source, and hence all except those at the head *are thrust forward.* Herein appears to lie the distinctive nature of glacial movement. Each part of a stream of water feels (1) the hydrostatic pres-

[1] For fuller discussion, see the authors' *Geologic Processes*, pp. 308-321.

sure of neighboring parts (theoretically equal in *all* directions), and (2) the momentum of motion, but *not the thrust of the water up stream.* This is probably one of the fundamental differences between water flow and glacier motion.

Lava streams are good examples of viscous fluids flowing in masses comparable to those of glaciers, on similar slopes, and, in the last stages of motion, at similar rates; but their special modes of flow and their effects on the sides and bottoms of their paths are radically different from those of glaciers. Forceful abrasion, and particularly the rigid holding of imbedded stones which score and groove the rock beneath, is unknown in lava streams, and is scarcely conceivable. There is, so

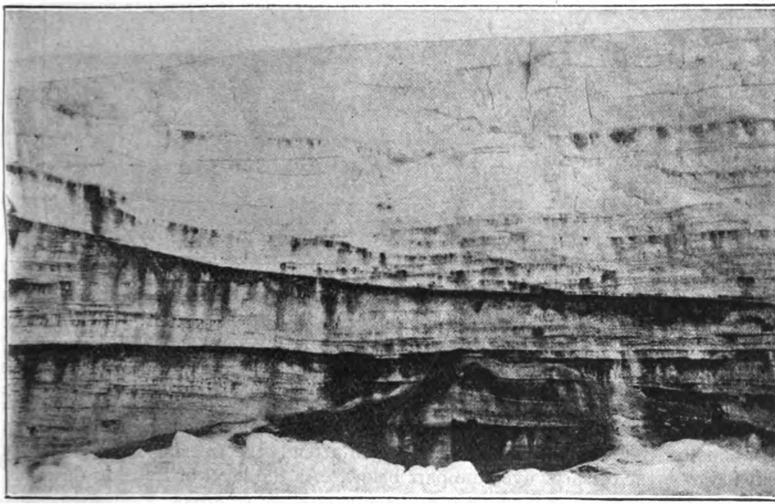


**Fig.** 143. A well defined shearing plane in a Spitzbergen glacier. (Hamberg.)

far as we know, no experimental or natural evidence that any viscous fluid, in the ordinary sense of that term, detaches and picks up fragments and holds them firmly as graving tools in its base so as to cut deep, long, straight grooves in the hard bottom over which it flows. It would seem that competency on the part of a viscous body to do this peculiar class of work so distinctive of glaciers should be demonstrated before the viscous theory of glacial movement is accepted as even a good working hypothesis. In contrast with viscous movement, it is conceived that a glacier is thrust forward rigidly by internal elongation, and that it is sheared forcibly over its sides and bottoms, leaving its distinctive marks upon them.

*Shearing.* In the terminal part of a glacier, where the thrusts are greatest, where the granules are fewest and their interlocking most intimate, shearing takes place within the ice. This is illustrated by Figs. 143 and 144. The shearing results in the foliation of the ice, and in the dragging of debris along the planes of shear. Shearing is observed chiefly where the ice below the plane of shearing is protected more or less from the force of the thrust, as in the lee of a hill or mass of

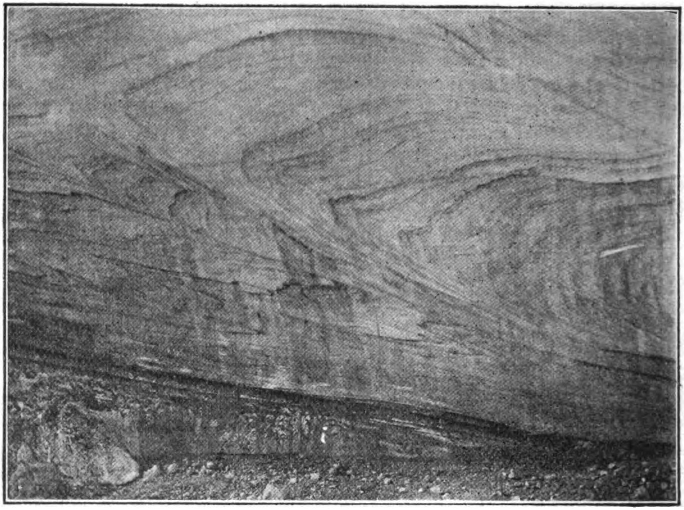


Fig. 144. Portion of the east face of Bowdoin Glacier, North Greenland, showing oblique upward thrust, with shear.

débris. It perhaps occurs also at the top of the basal zone of ice so loaded with débris that it is incapable of ready movement[1].

It is probable, also, that sharp differential strains and shearing are developed at the level where the surface water of the warm season, sinking into the ice, reaches the zone of freezing; for the expansion which attends the freezing may cause the expanding layer to shear over the part below. As the level of freezing descends with the advance of the warm season, the zone of shearing sinks.

Expansion at the zone where descending water freezes not only leads to shear, but to the development of surface cracks, for the surface is stretched as the zone below expands. In the course of years, the cracks developed in this way may become wide crevasses, limited below by the depth of the zone of freezing in summer.

*High temperature and water.* Toward the lower end of a glacier, the higher temperature and the greater abundance of water lend their aid to the fundamental elements of movement. During the warm season, the ice here is bathed in water all the time, so that the necessary changes in the crystals are facilitated. Under these conditions, movement takes place more readily than in the drier, colder and more open, granular ice of lower temperature, near the source of the glacier.

*Application.* The co-operation of these several factors appears to explain the peculiarities of glacial movement. In regions of intense cold, where a dry state and low temperature prevail, as in the heart of Greenland, the snow-ice mass may

[1] The crystals of ice have a peculiar structure which has been thought by some to be an important factor in shearing, and so in the motion of glaciers ice. See the authors' *Geologic Processes*, p. 312; also (10) p. 323.

attain extraordinary thickness. Here the burden of movement seems to be thrown almost wholly on compression, with the slight aid of molecular changes due to internal evaporation. Since the temperature in the upper part of the ice is very low most of each year, the compression must be great before it becomes effective in melting; hence the great thickness of ice necessary before motion is considerable. Similar conditions affect the heads of Alpine glaciers, though here the high gradients favor motion among the granules of ice. In the lower reaches of Alpine glaciers, where the temperatures are near the melting-point, and where the ice is bathed in water much of the time, movement may take place in ice which is thin and compact.

If the views here presented are correct, there is also, at all points below the source, the co-operation of rigid thrust from behind, with the tendency of the mass to move on its own account. The latter is controlled by gravity, and conforms *in its results* to laws of liquid flow. The former is a mechanical thrust. This thrust is different from the pressure of the upper part of a liquid stream on the lower part, because it is transmitted through a body whose rigidity is effective, while the latter is transmitted on the hydrostatic principle of equal pressure in all directions. Thrust would be most effective toward the end or edge of a glacier.

*Corroborative phenomena.* The conception of the glacier and its movement here presented explains some of the anomalies that otherwise seem paradoxical. If the ice is always a rigid body which yields only as its interlocking granules change their form by loss and gain, a rigid hold on the imbedded rock at some times, and a yielding hold at others, is intelligible. Stones in the base of a glacier may be held with great rigidity when the ice is dry, scoring the bottom with much force, while they may be rotated with relative ease when the ice is wet. In short, the relation of the ice to the bowlders in its bottom varies radically according to its dryness and temperature. *A dry glacier is a rigid glacier. A dry glacier is necessarily cold, and a cold glacier is necessarily dry.*

It is difficult to explain the furrows and grooves cut by glaciers in firm rock if the ice is so yielding as to flow under its own weight on a surface which is almost flat. If the mass is really viscous, its hold on its imbedded debris should also be viscous, and a bowlder in the bottom should be rotated in the yielding mass when its lower point catches on the rock beneath, instead of being held firmly while a groove is cut. This is especially to the point since viscous fluids flow by a partially rotary movement.

On the view here presented, a glacier should be more rigid in winter than in summer. The total thickness of a glacier should experience this rigidity of winter at its ends and edges, where the ice is thin enough to permit the low temperature to affect its bottom. The motion in these parts during the winter is, therefore, very small.

In this view, also, may be found an explanation of the movement of glaciers for considerable distances up-slope, even when the *surface* of the ice, as well as its bed, is inclined backwards. So far does this go, that a few superglacial streams run for some distance *backwards*, i. e., toward the heads of the glaciers, while in other places surface waters are collected into ponds and lakelets. Such a slope of the surface of ice is not difficult to understand if the movement is due to thrust from behind, or if it is occasioned by internal crystalline changes acting on a rigid body; but it must be regarded as very remarkable if the movement of the ice is that of a fluid body, no matter how viscous, for the length of the acclivity is in some cases several times the thickness of the ice. Crevassing and other evidences of

brittleness and rigidity find a ready elucidation under the view that ice is really a solid body at all times, and that its apparent fluency is due to the momentary fluidity of small portions of its mass assumed in succession as compression demands.

In addition to the considerations already adduced, it may be urged that a glacier does not flow as a stiff liquid because its granules are not habitually drawn out into elongated forms, as are cavities in lavas, and plastic lumps in viscous bodies. Flowage lines comparable to those in lavas are unknown in glaciers.

All this is strictly consistent with our primary thesis, that a glacier is crystalline rock of the purest and simplest type, and that it never has other than the crystalline state. This strictly crystalline character is incompatible with viscous liquidity.

*Other views of glacier motion.* While these views of glacial motion seem to us to accord best with the known facts, they are not to be regarded as established in scientific opinion, or as the views most commonly held. The main alternative interpretations that have been entertained are the following:

(1) In the early days of glacial studies De Saussure thought that glaciers slid bodily on their beds.

(2) Charpentier and Agassiz referred the movement to the expansion of descending water freezing within the glacier.

(3) Rendu and Forbes, followed by many modern writers, believed ice to be viscous, and that in sufficiently large masses it flows under the influence of its own weight, like pitch or asphalt.

(4) Others, realizing the fundamental difference between crystalline ice and a true viscous body, have fallen back on a vague notion of plasticity, which scarcely amounts to a definite hypothesis at all.

(5) Tyndall urged that the movement was accomplished by minute repeated fracturing and regelation, appealing to the fact that broken pieces of ice slightly pressed together at melting temperatures freeze together, but neglecting the fact that this would destroy the integrity of the crystals.

(6) Moseley assigned the movement to a bodily expansion and contraction of the glacier, analogous to the creeping of a mass of lead on a roof.

(7) James Thompson demonstrated that pressure lowers the melting-point, and while this effect is so small as probably to be ineffectual, it is correlated with the very important fact that compression, by generating heat, may cause melting, which is not the case in most other rocks. He recognized that under pressure partial liquefaction took place, that the water so liberated might be refrozen as it escaped from pressure, and appears to have regarded this as a vital factor.

(8) Croll held that the movement was due to a consecutive series of molecular changes somewhat like the chain of chemical combinations in electrolysis.

(9) Hugi, Eli de Beaumont, Bertin, Forel, and others thought that the growth of the granules was the leading factor in ice movement.

(10) McConnel and Mügge have made the gliding planes of the ice crystals serve an important function in glacial movement.

It will be seen that the principle of partial liquefaction for which Thompson laid the basis, the crystallization of descending water urged by Charpentier and Agassiz, and the granular growth on which Hugi, Beaumont, Forel, and others founded their hypotheses, are incorporated in the view already presented. Probably the agencies on which some of the other views are based may also be participants in producing glacial motion, in some places as incidental factors, and in others perhaps as important ones.

## THE WORK OF GLACIERS

### *Erosion*

Glaciers abrade the valleys through which they pass, carry forward the material which they remove from the surface, and wear, grind, and ultimately deposit it. Like other agents of gradation, their work includes erosion, transportation, and deposition.

**Getting load.** If the snow-field which is to become a glacier accumulates on a rough surface covered with rock debris, the glacier has a basal load when it begins to move, for the snow covers, surrounds, and includes such loose blocks of rock as project above the general surface, and envelops all projecting points of rock within its field. When the ice begins to move, it carries forward this debris in its bottom, and tears off the weak points of rock which project up into it. In addition to the *basal* and *sub-glacial* load which the glacier has at the outset, there may be surface debris which has fallen on the snow or ice from cliffs above. If debris descending to the glacier in this way is unburied, it is *superglacial*, but if it has been buried by subsequent falls of snow, it is *englacial*.

Once in movement, the ice not only moves the debris to which it was originally attached, but it gathers new load, partly by the rasping effect of its rock-shod bottom, and partly by its power of plucking off or quarrying out considerable blocks of rock from its sides and bottom. This plucking process is at its best where the ice passes over cliffs of jointed rock, but is not confined to such situations. The steep bed of a valley glacier may be worn more by plucking than by rasping. The advancing ice gets some material, too, especially loose debris, by freezing to it, for the water in the soil freezes and becomes continuous with the ice above, and moves with it. Superglacial material may be acquired during movement, as well as before it, by the fall of debris from cliffs, or by the descent of avalanches.

**Conditions influencing rate of erosion.** (1) Ice wears a flat surface relatively little, since there is little for it to get hold of. Glaciers have been known to override such a surface, burying its soil and more or less of its herbaceous vegetation. Erosion is at its maximum, so far as influenced by topography, when the surface is rough enough to offer notable catchment for the base of the ice, but not so rough as to impede its motion seriously. Other conditions which influence glacial erosion are (2) the amount of loose or slightly

attached debris on the surface; (3) the slope of the surface; (4) the thickness of the ice; (5) its rate of movement; (6) the resistance of the rock; and (7) the amount and kind of debris the ice carries. The effect of most of these conditions is evident, but the last two call for a word of explanation.

So far as concerns the resistance of the rock, it should be noted that resistance is not a matter of hardness simply. Rock which is affected by cleavage, whether joints or bedding planes or both, is eroded readily, expecially on steep slopes, even if very hard. In

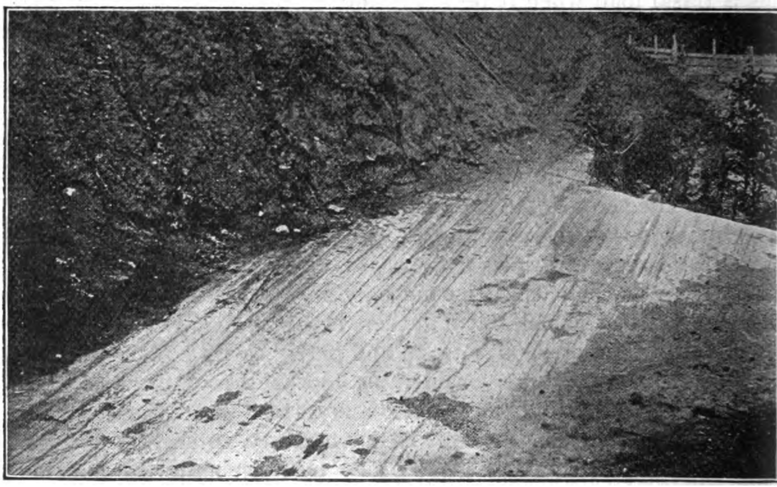


Fig. 145. Striæ on bed-rock. Kingston, Des Moines County, Iowa.

such situations, the removal of rock in large blocks (*plucking*) is probably more important, on the whole, than wear by the debris carried.

Clean ice passing over a smooth surface of solid rock would have little effect upon it; but a rock-shod glacier abrades the same surface notably. The effect of this abrasion is shown in the grooves and scratches (*striæ*) which the stones in the bottom of the ice inflict on the surface of the rock over which they pass (Figs. 145 and 146). At the same time, the stones in the ice are worn by abrasion both with the bottom, and with one another (Fig. 147). It does not follow, however, that erosion is greatest when there is most material in the bottom of the ice; for with increase of debris there may be

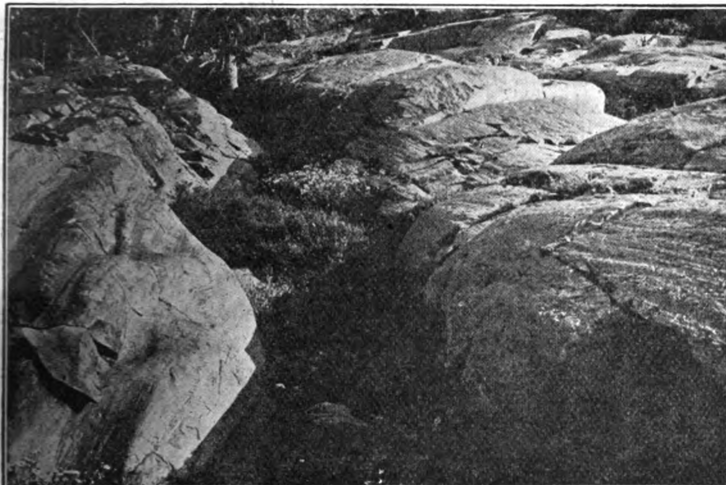


Fig. 146. Striæ, grooves, etc., in a canyon tributary to Big Cottonwood Canyon, Wasatch Mountains. (Church.)

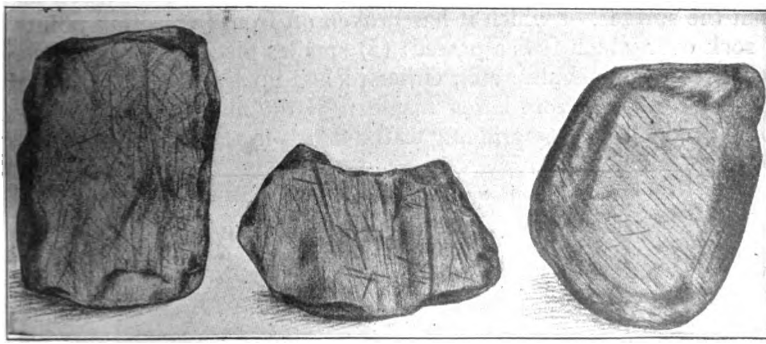


Fig. 147. Stones striated by glacial wear. Their shapes, as well as their markings, are characteristic.

decrease of motion,[1] and decrease of motion retards erosion. When any considerable thickness of ice at the bottom of a glacier is full of debris, the loaded part may approach stagnancy, while the cleaner ice above shears over it. A moderate but not excessive load of debris, therefore, favors great erosion. Something depends, too, on the character of the load. Coarse, hard, and angular debris is

[1] Russell. Jour. of Geol., Vol. III, p. 823.

more effective for abrasion than fine, soft, or rounded material. In plucking, rate of motion is probably more important than load.

So far as concerns the ice itself, erosion is not most effective at the end of a valley glacier, or at the edge of an ice sheet, for here the strength of movement is too slight and the load too great; nor is it most effective at the source or near it, for the ice here moves slowly and its load is likely to be slight. Ice alone considered, erosion is most effective somewhere between the source and the terminus of a glacier, and probably much nearer the latter than the former.

In summary it may be said that rapidly moving ice of sufficient thickness to be working under goodly pressure, shod with a sufficient but not excessive quantity of hard-rock material, passing over non-resistant formations possessing a topography of sufficient relief to offer some resistance, and yet too little to retard the progress of the ice seriously, will erode most effectively.

**Varied nature of glacial debris.** From its mode of erosion it will be seen that a glacier may carry various sorts of material. At its bottom there may be (1) bowlders which the ice has picked up from the surface, or which it has broken off from projecting points of rock over which it has passed; (2) smaller pieces of rock of the size of cobbles, pebbles, etc., either picked up by the ice from its bed or broken off from larger masses; (3) the fine products (rock-flour) produced by the grinding of the debris in the ice on the rock-

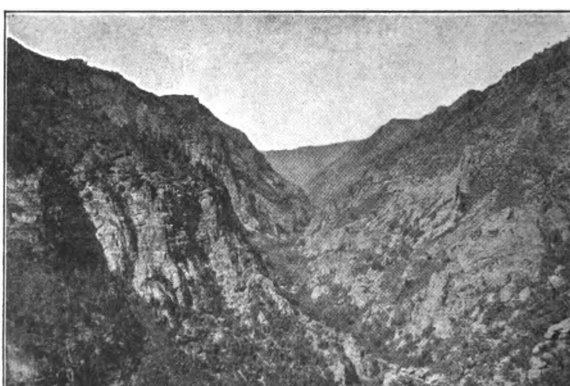


Fig. 148. A mountain valley in the Wasatch Mountains, not glaciated. (Photo. by Church.)

bed over which it passes, and similar products resulting from the rubbing of stones in the ice against one another; and (4) sand, clay, soil, vegetation, etc., derived from the surface overridden. Thus the materials which the ice carries (called *drift*) are of all grades of coarseness and fineness, from huge bowlders to fine clay. The coarser materials may be angular or round at the outset, and their forms may be changed and their surfaces striated as they are moved forward. Whether one sort of material or another predominates depends primarily on the nature of the surface overridden.

**The topographic effects of glacial erosion.** In passing through its valley, an alpine glacier deepens it, widens its lower part, and smoothes its slopes up to the limit of the ice. It tends to make a

Fig. 149. A mountain valley which has been strongly glaciated, Wasatch Mountains. (Photo. by Church.)

V-shaped valley (Fig. 148) U-shaped (Fig. 149), and to make its head big, blunt, and steep-sided. Such a valley head is a *cirque* (Pl. XIII). The change in topography at the upper limit of glaciation is striking in many places (Fig. 150).

The deepening of a valley by glacial erosion may throw its tributaries out of topographic adjustment. Thus if a main valley is lowered 100 feet by glacial erosion while its tributary is not deepened, the lower end of the latter will be 100 feet above the former when the ice disappears. Such valleys, called *hanging valleys* (Fig. 151), are common in the western mountains of North America which were recently glaciated.

Ice-caps which overspread the surface irrespective of valleys and hills tend to reduce angularities of surface. Hills and ridges are cut down and smoothed (Figs. 152 and 153); but since valleys

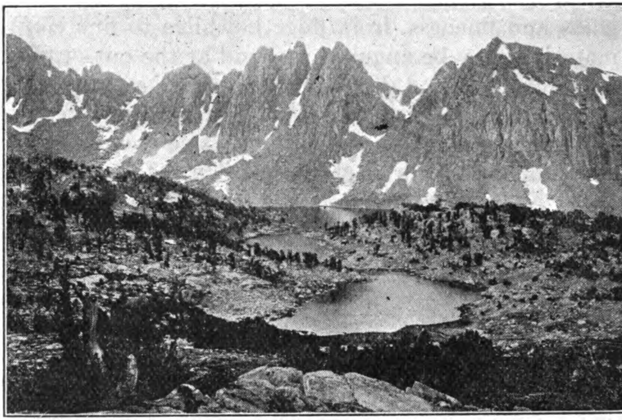


Fig. 150. Contrast between a glaciated rock surface below, and non-glaciated crests above. Kearsarge Pinnacles, Bubbs Creek Canyon, Cal.

parallel to the direction of movement are deepened at the same time, it is doubtful if the relief is commonly reduced by the erosion of an ice-cap.

**Fiords.** A valley glacier descending to the sea may gouge out

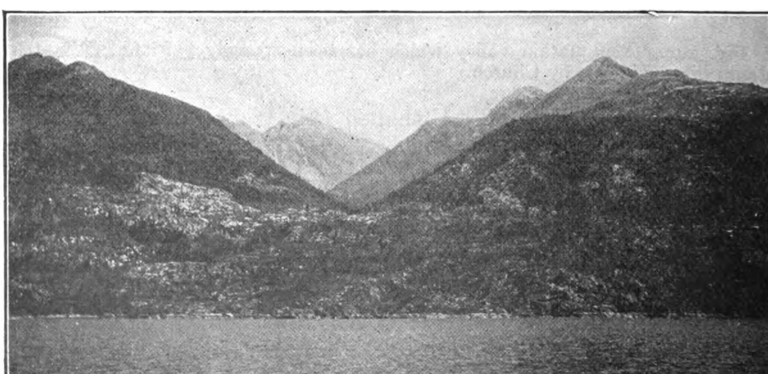


Fig. 151. A hanging valley near Lake Kootenay. (Photo. by Atwood.)

the head of a bay or the lower end of a valley to a very considerable depth. When the ice melts, the bay, if narrow, deep, and long, with high slopes, is called a *fiord*. Many of the fiords of coasts in high latitudes originated in this way, and some glaciers of these coasts are now making fiords. Sinking accompanying or following glaciation, is also a factor in the making of fiords.

Fig. 152. Diagram representing a hill unworn by ice, and the irregular contact of soil and rock.

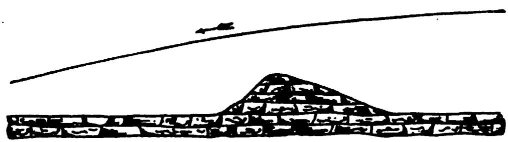


Fig. 153. Diagram showing the effect of glacial wear on a hill such as is shown in Fig. 152.

**The positions in which debris is carried.** Debris is carried in three positions: (1) *basal* or *subglacial*, (2) *englacial*, and (3) *superglacial*. The material picked up or rubbed off from the surface over which the ice moves is normally carried forward in the bottom of the ice, and is therefore basal; that which falls on the surface is usually carried there, and is therefore superglacial. Either basal or super-glacial drift may become englacial. The basal load of a glacier is constantly being mixed with new drift from the ground over which the ice is passing. The superglacial material, on the other hand, may be borne from its place of origin to its place of deposition without such intermixture.

**Transfers of load.** Superglacial debris obviously may become englacial or basal by falling into crevasses, or by being carried down by descending waters.

Debris which is basal *at the outset*, may become englacial or superglacial later. Thus when ice passes over a hill, the bottom of the ice rends debris from its top. To the lee of the hill the ice from either side may close in under that which came over the top. The debris derived from the top of a hill by the bottom of the overriding ice will then be well up in the ice (Fig. 154).

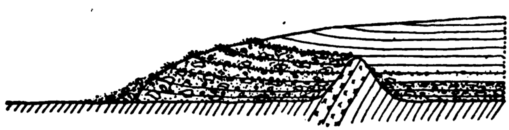


Fig. 154. Diagram illustrating one way in which a glacier gets englacial material.

Englacial drift may become superglacial by surface ablation. In this case the drift does not rise, but melting brings the surface of the ice down to it. This occurs chiefly at the end or edge of the ice, where the surface melting is greatest. Englacial debris, especially that near the bottom, also may become basal by the melting of the ice beneath it.

Drift is sometimes transferred from a basal to an englacial and then to a superglacial position by upward movement. Such transfer is the more remarkable because the specific gravity of rock is about three times that of ice, so that the normal tendency of rock is to sink in ice. In arctic glaciers, and probably in others, some material which has been basal becomes englacial by being sheared forward over ice in front of it. So far as observed, this takes place chiefly where the ice in front of the plane of shearing lies at a lower level than that behind, as where the surface of an upland falls off into a valley, or where a boss of rock shelters the ice in its lee from the thrust of the overriding ice (Fig. 155).

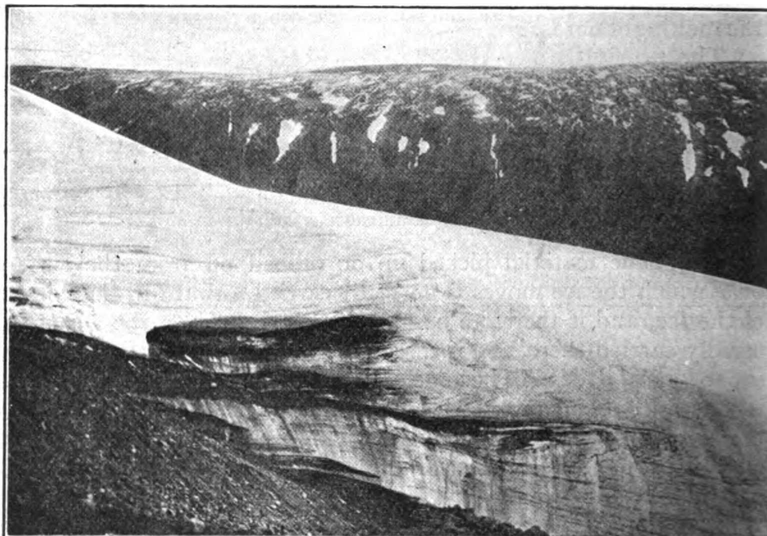


Fig. 155. Taking debris from a protuberance of the bed.

At the borders of many arctic glaciers the lower layers are turned up, as shown in Fig. 156. Where the layers turn up at the end of a

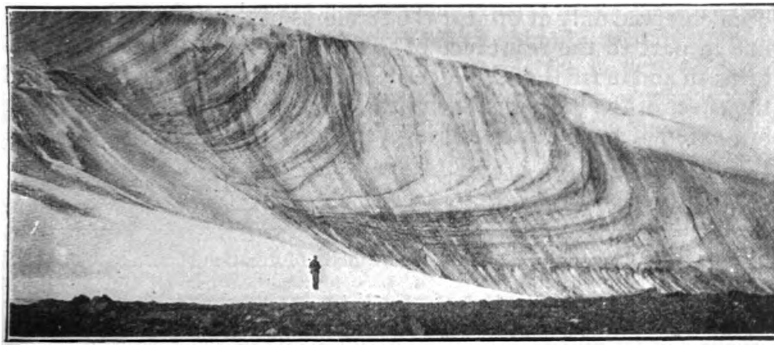


Fig. 156. End of a North Greenland glacier, showing the upturning of the layers of ice at the end. This structure is common in North Greenland. At one point, a few stones are seen on the surface of the ice where an upturned layer comes to the surface.

glacier, basal and englacial debris are carried to the surface by actual upward movement, and a terminal moraine or a series of terminal moraines may be developed *where the upturned layers of ice outcrop at the surface* (Fig. 157). That the material of these moraines was originally basal is shown in many cases by the bruised and scratched

Fig. 157. Surface terminal moraines due to upturning. Edge of the ice-sheet, North Greenland.

condition of the bowlders and pebbles, or by the nature of the material itself. The upturning may affect the edges of glaciers (Fig. 158) as well as their ends, and the material thus brought to the surface gives rise to lateral moraines. In some cases, too, there is upturning of the ice along a longitudinal zone well back from the lateral margins (Fig. 158), and the material brought to the surface in such a zone gives rise to a medial moraine. This upturning of ice has

been observed only at or near the terminus of the ice. It perhaps is due in part to the resistance of frozen morainic or other material beneath and in front of the edge. To this should probably be added the effect of the great rigidity of the outer part of the ice due to the low external temperature during the larger part of the year, while

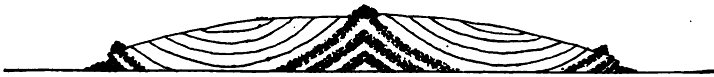


Fig. 158. Diagram to illustrate one method of formation of medial and lateral moraines. The horizontal line at the base represents sea-level, and the lower part of the glacier is under the sea. The layers of upturning ice bring debris up along the planes of movement, and it accumulates at the top as indicated.

the interior, with its higher temperature, remains more fluent; but even this probably leaves the explanation incomplete.

**Wear of drift in transit.** Drift carried at the bottom of the ice is much worn, for the materials in transit abrade one another and are abraded by the bed over which they pass. Englacial drift is subject to less wear, because it commonly is more scattered. Superglacial drift is worn little or none while it lies on the surface of the ice; but in so far as superglacial or englacial drift is derived from basal drift, it may show the same evidences of wear as the basal drift itself. In many cases superglacial drift reveals its history in this way.

### *Deposition*

During the advance of a glacier, deposition takes place both (1) beneath the body of the ice, and (2) beneath its end and edges. In the former position it takes place where the topography favors lodgment, or where the ice is overloaded. The topography favoring deposition is much the same as that favoring erosion, but the two processes are not favored at the same points. Erosion is greatest on the "stoss" side (the side against which the ice advances) of an obstruction, and deposition on the lee side (Fig. 159). Glacier ice

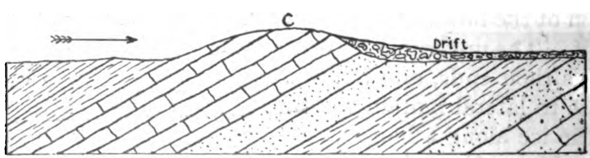



Fig. 159. Crag and tail. The passage of glacier ice is likely to leave drift in the lee of the boss of rock, C.

is likely to be overloaded (1) just beyond a place where conditions have favored erosion, and (2) where the ice is thinning rapidly. On the whole, deposition beneath the body of a glacier back from its

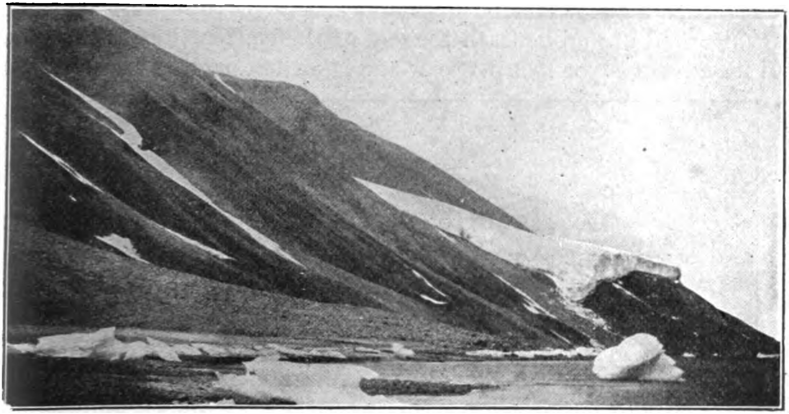


Fig. 160. Glacier building an embankment. Southeast side of McCormick Bay, North Greenland.

end or edge, is much more than balanced by erosion in the same position.

At and near the end of a glacier, deposition goes on faster than elsewhere, chiefly because of the rapid melting, and therefore the thinning and weakening of the ice. If the end of the glacier is stationary in position, drift is being brought to it continually and

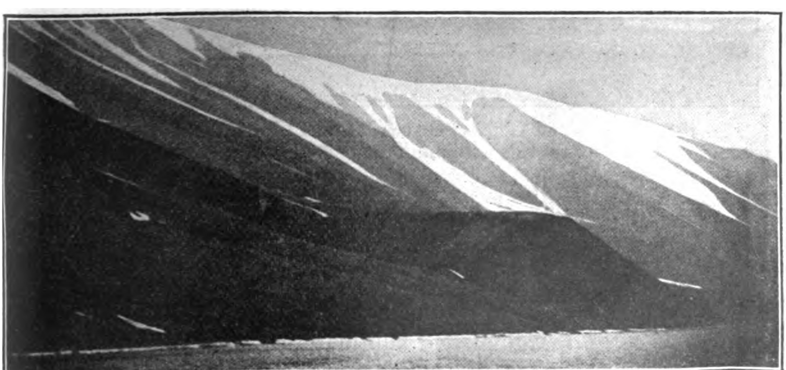


Fig. 161. Embankment completed. Near the last. (Fig. 160.)

left there, for it is to be remembered that the ice is moving, though its end is stationary. If a glacier moves forward 500 feet per year, while its end is melted at the same rate, all the debris in the 500 feet of ice melted, is deposited, and all except that washed away is deposited at and beneath the end of the glacier (Figs. 160–161). If ice advances 500 feet per year and is melted back 600 feet in the

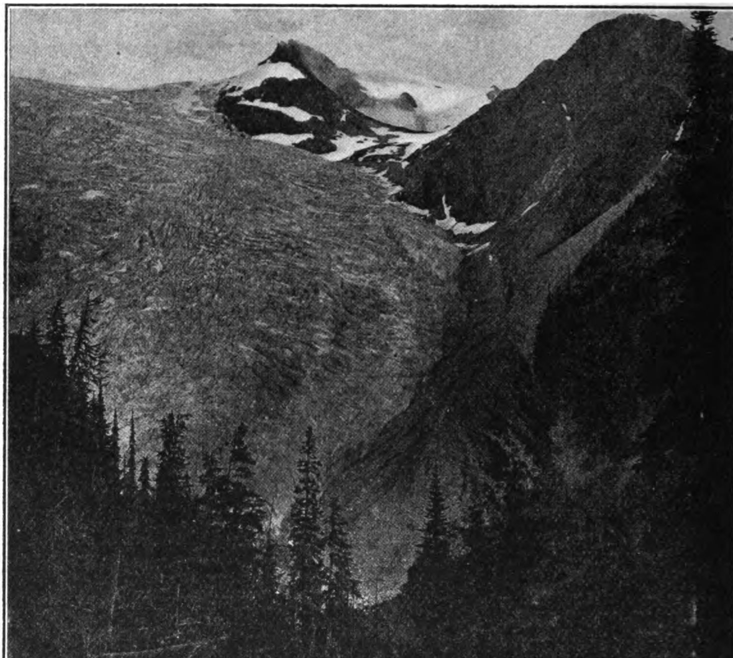


Fig. 162. Illecillewæt Glacier; Glacier, British Columbia. A lateral moraine at the right of the ice records its diminution.

same time, all the debris carried by the 600 feet melted has been deposited, and largely in the narrow zone (100 feet) from which the ice has receded. If the end of a glacier advances 500 feet per year while it is being melted but 400 feet, all the drift in the 400 feet melted is deposited, chiefly at or beneath the immediate margin of the ice. To the marginal and sub-marginal accumulations made in this way, the material carried on the ice is added whenever the ice is melted from beneath it. Deposition beneath the lateral

Fig. 163. The moraines about the lower end of a glaciated mountain valley. Bloody Canyon, Cal. (U. S. Geol. Surv.)

margins of a glacier is much the same as beneath its terminus (Fig. 163).

### *Types of Moraines*

**The terminal moraine.** The thick accumulation of drift made at the end of a glacier or at the edge of an ice sheet, especially where its end or edge is stationary or nearly so for a long time, is the *terminal moraine.* Terminal moraines of ice caps are of more importance, relatively, than those of valley glaciers, for streams are more effective in destroying the moraines of the latter. The topography of terminal moraines is rather distinctive, as illustrated by Fig. 168.

**The ground moraine.** When a glacier disappears, all its debris is deposited. All drift deposited beneath the body of the ice, and all deposited from its base during dissolution, constitutes the *ground moraine.* The thickness of the ground moraine is notably unequal. In general, it is thicker toward the terminus of the glacier and thinner toward its source, but considerable portions of a glacier's bed may be left without debris when the ice melts. As a rule, the ground moraine is thinner than the terminal moraine, and less irregularly disposed. The ground moraines of valley glaciers are relatively unimportant as compared with those of ice-caps, since conditions for erosion under the body of a valley glacier are, on the average, better than under an ice-sheet, while those for deposition

are less favorable. The topography of the ground moraine (Plate XIV) is, as a rule, less uneven than that of the terminal moraine (Fig. 168).

**Lateral moraines.** Lateral moraines are the product of valley glaciers. The lateral moraines on such glaciers are let down on the surface beneath when the ice melts; but the lateral moraines in a valley from which the ice has melted are not merely the lateral moraines which were on the glacier. They are made up chiefly of drift accumulated beneath the sides of the glacier. This accumulation is the result of the lateral motion of the ice from the center to

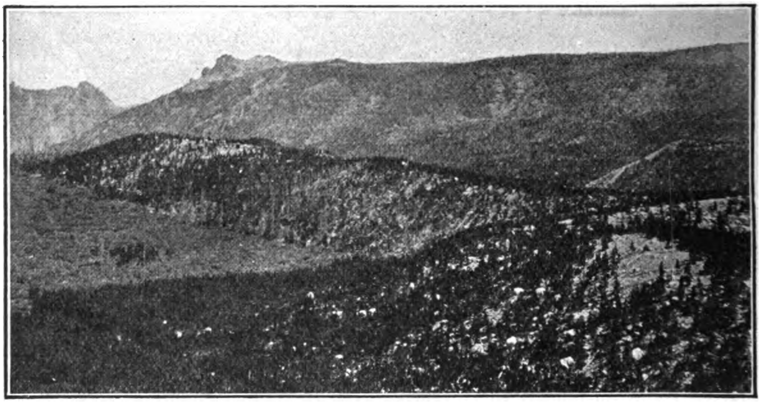


Fig. 164. A lateral moraine lett by a former glacier in the Bighorn Mountains of Wyoming. (Photo. by Blackwelder.)

the sides of the valley. Such sub-lateral accumulations are akin to terminal moraines. Some of the lateral moraines of ancient valley glaciers, those like of the Uinta, Wasatch, and Bighorn mountains are several hundred feet high (Fig. 164), or even as much as a thousand. In northern Italy a lateral moraine is said to be more than 2,000 feet high.[1]

**Distinctive nature of glacial deposits.** The deposits made by glaciers are distinctive. In the first place, the ice does not assort its drift, and bowlders, cobbles, pebbles, sand, and clay are confusedly commingled (Fig. 165). In this respect, the deposits of ice differ notably from those of water. Furthermore, many stones of the drift show the peculiar type of wear which glaciers inflict.

[1] Geikie. The Great Ice Age, 3d ed., p. 529.

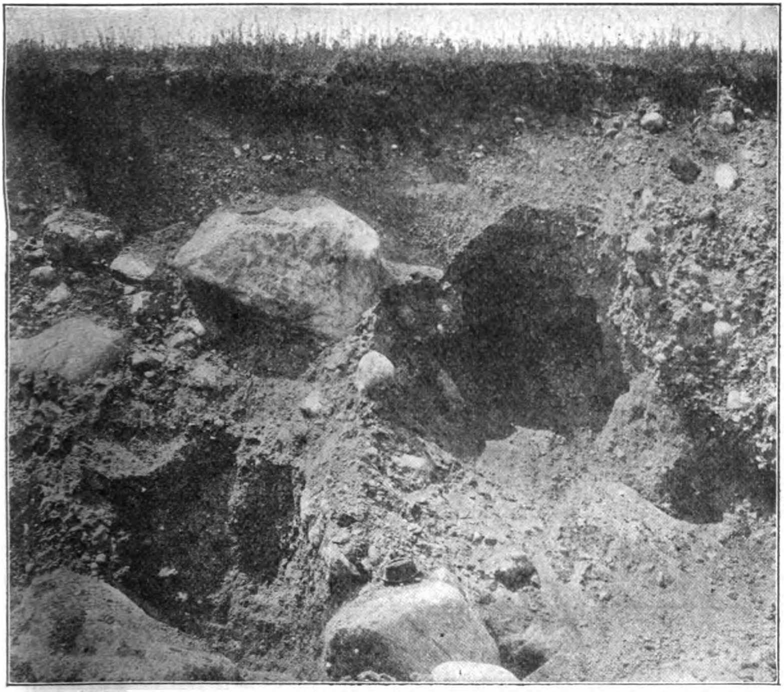


Fig. 165. Section of drift showing its heterogeneity.

Though notably worn, they are not rounded like the stones carried by rivers. Many of them have sub-angular forms with planed and beveled faces, the planes being striated and bruised (Fig. 147). Absence of stratification, physical heterogeneity, and the striation of at least a part of the stones are among the most distinctive characteristics of glacial drift. A not less real though less obvious characteristic is the constitution of the fine material, for it is, as a rule, the product of rock grinding, not of rock decay.

**Glaciated rock surfaces.** Another distinctive mark which a glacier leaves behind it is the character of the surface of the rock on which the drift rests. This is generally smoothed by the severe abrasion to which it has been subjected, and the smoothed surfaces (Figs. 145 and 166) are marked by grooves and striæ, similar to those on the stones of the drift (Fig. 147). Other distinctive features of a glaciated area are rounded bosses of rock (*roches mouton-*

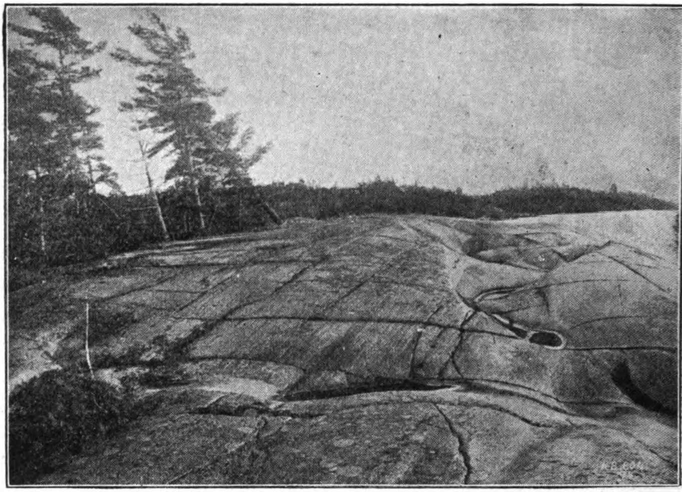


Fig. 166. Ice-worn rock, Bell's Island, Lake Huron. (Bell.)

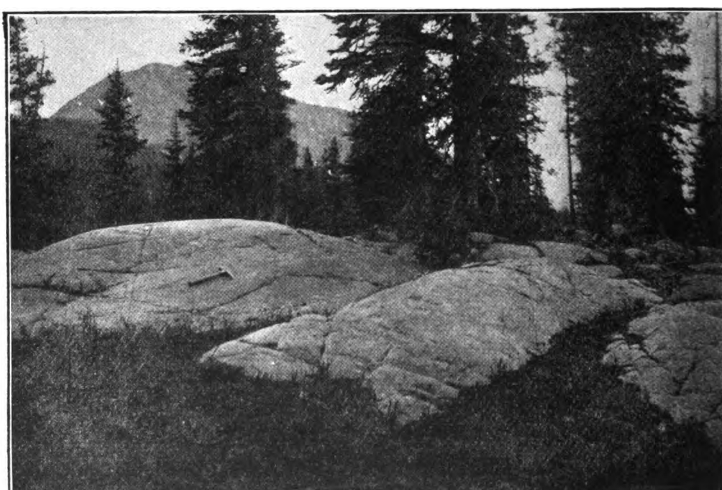


Fig. 167. Roches moutonnées, Engineer Mountain, Colo. (Hole, U. S. Geol. Surv.)

*nées*, Fig. 167), rock basins, ponds, and marshes, and the peculiar topographies resulting from the unequal erosion (Pl. XIII), and the still more unequal deposition (Fig. 168) of drift. Surface bowl-

Fig. 168. Sketch of drift (terminal moraine) topography near Hackettstown, N. J. (N. J. Geol. Surv.)

ders, in many cases unlike the underlying formations of rock, and sometimes in peculiar and apparently unstable positions (*perched bowlders*) are still another mark of a glaciated area (Fig. 169).

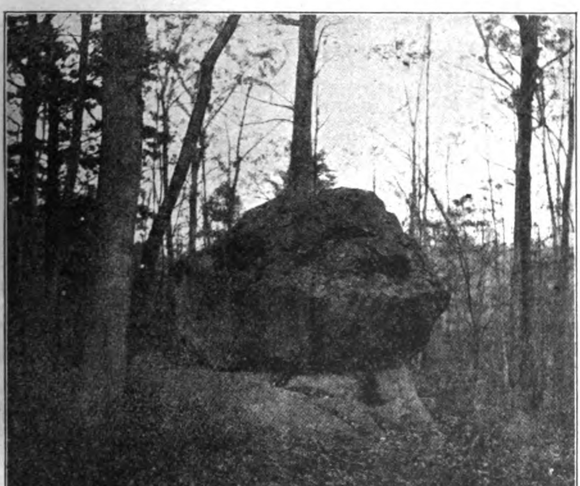


Fig. 169. Perched bowlder, New Jersey.

GLACIO-FLUVIAL WORK

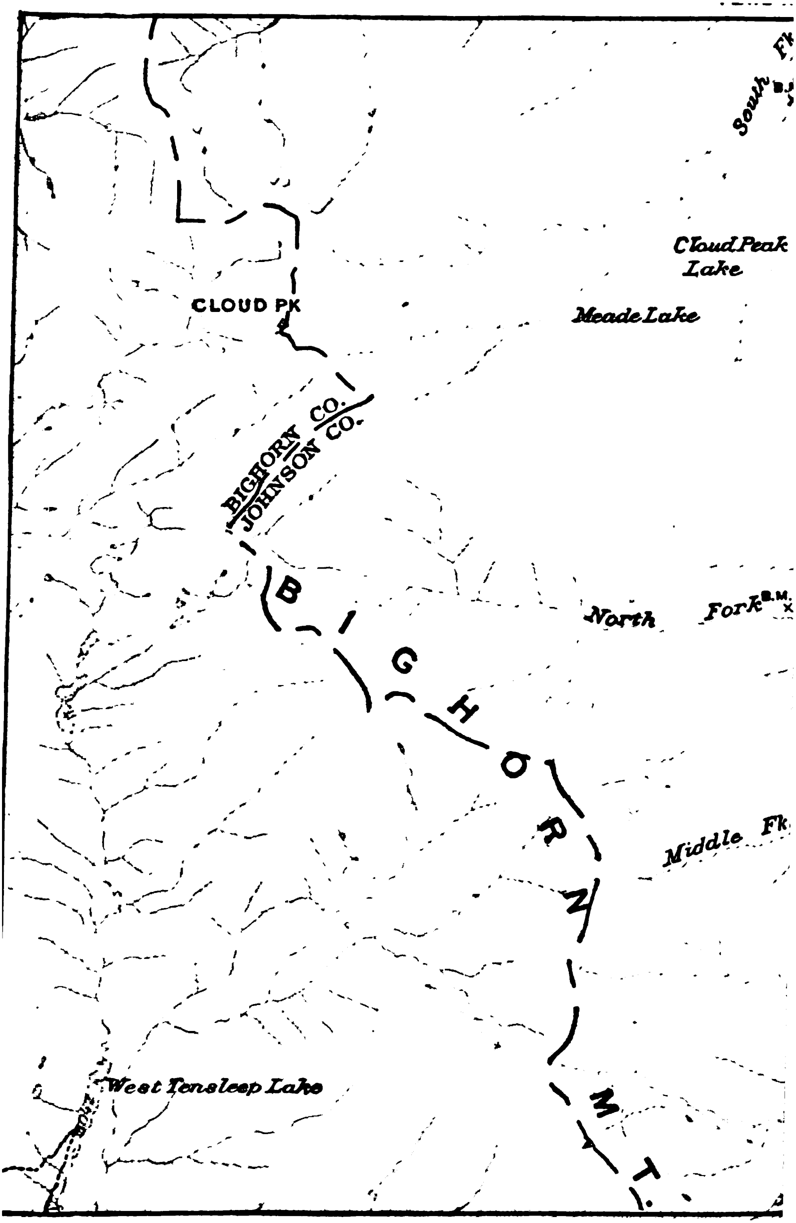
The streams to which the melting of the ice gives rise are laden with gravel, sand, and silt derived from the ice. Where the mud is light-colored, the streams are sometimes described as "milky." Where the amount of material carried is great, much of it is dropped at a slight distance from the ice, the coarsest being dropped first. Glacial streams are, as a rule, aggrading streams, and therefore develop alluvial plains, called *valley trains* (Fig. 170), or, where they


Fig. 170. Diagram to illustrate the profile of a valley train, and its relations to the terminal moraine (*m*) in which it heads.

enter lakes, bays, or other streams, deltas. In its transportation, the river-borne drift is assorted, and after its deposition it is strati-

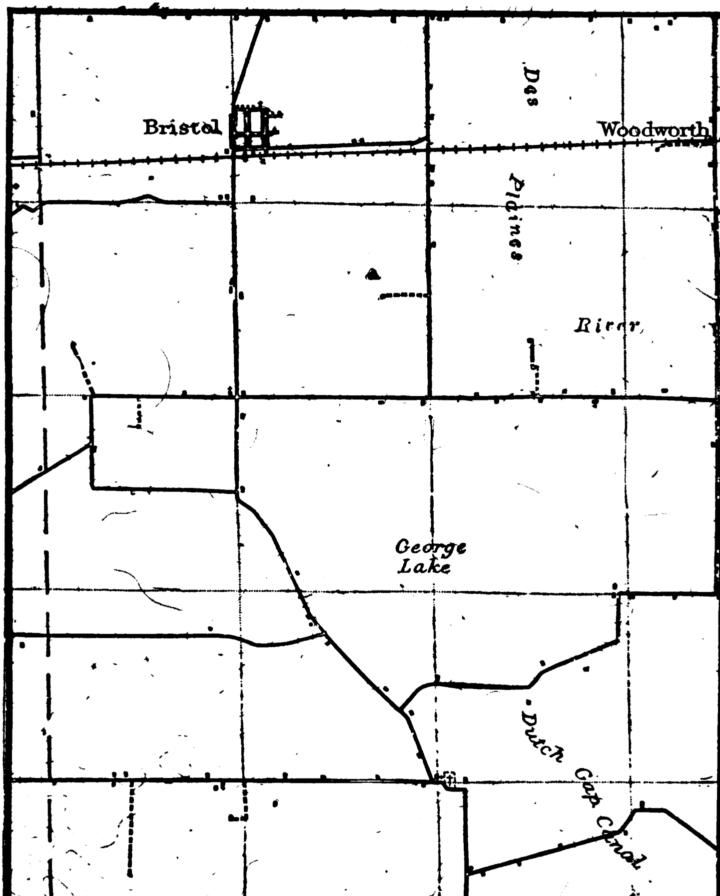
Fig. 171. Esker of Punkaharju, Finland.

fied. Glacial deposits in the upper part of a mountain valley are, therefore, generally connected with glacio-fluvial deposits farther down the valley. The silt, sand, and gravel of valley trains can, as a rule, be distinguished from valley deposits of non-glacial origin




A portion of the Bighorn Mountains, showing glaciated valleys, the heads of which are in many cases cirques. Scale, about 2 miles per inch. (Cloud Peak, Wyo., Sheet, U. S. Geol. Surv.)

PLATE XIV




Characteristic surface of a glaciated plain, showing marshes, ponds, and lakes. Southern Wisconsin. Scale, about 1 mile per inch. (Silver Lake, Wis., Sheet, U. S. Geol. Surv.)

by the fact that they are largely of undecayed rock material, especially if deposited recently.

Numerous streams flow from an ice-sheet, spreading their debris in front of the terminal moraine, forming a broad fringing sheet of gravel and sand (*outwash plain*) along it. Outwash plains have much in common with piedmont alluvial plains. They differ from valley trains chiefly in being shorter, wider, and not confined to valleys.

Where streams of considerable size form tunnels under the ice, the tunnels may become more or less filled with water-worn debris, and when the ice melts, the aggraded channels appear as ridges of gravel and sand, known as *eskers* (Fig. 171). It has been thought that eskers represent deposits formed in superglacial channels; but this is probably rarely if ever the case, for most surface streams have high gradients, swift currents, and smooth bottoms, and hence give little opportunity for lodgment. Furthermore, ice-sheets, in connection with which eskers are developed, have no surface material except at their immediate edges.

At the mouths of ice-tunnels or ice-channels, and in the re-entrant angles of the edge of the ice, sands and gravels are liable to be bunched in quantity, giving rise, after the adjacent ice has melted, to peculiar hills and hollows of knob-and-basin type. The hills and short ridges of stratified drift formed in this way are known as *kames*. Much stratified drift (gravel, sand, and silt) deposited by glacial streams has no distinctive topographic form, and therefore no special name.

All fluvio-glacial deposits are stratified. Kames and eskers made in immediate association with the ice, and more or less affected

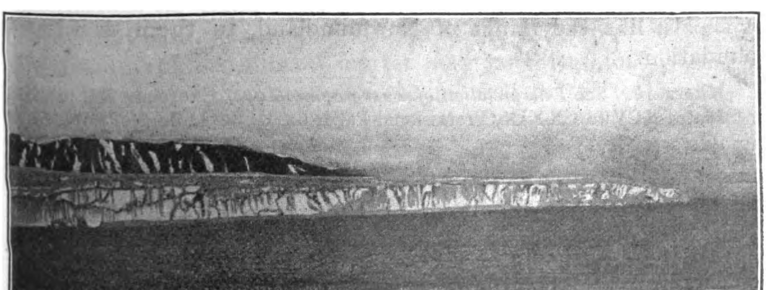


Fig. 172. The end of a glacier in Spitzbergen. (Rabot.)

by its movements, are less perfectly and regularly stratified than valley trains and outwash plains.

### ICEBERGS

Where glaciers advance into water the depth of which approaches their thickness, their ends are broken off (Fig. 172), and the detached masses float away as icebergs (Fig. 173). Many of the bergs

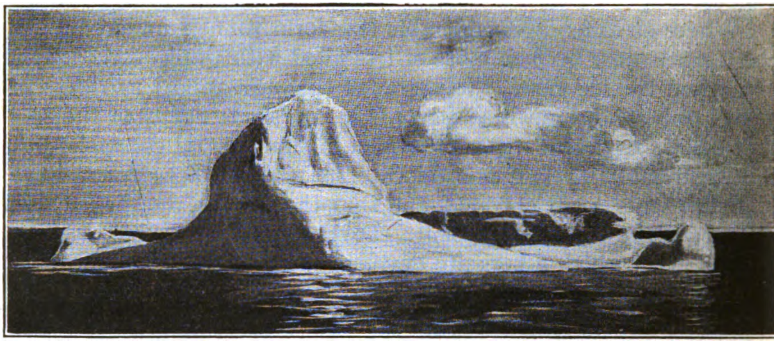


Fig. 173. An iceberg. (Robin.)

are overturned, or at least tilted, as they set sail. If this does not happen at the outset, it may later, as the result of melting, wave-cutting, etc., which shift the centers of gravity of the bergs. The great majority of them do not float far before losing all trace of stony and earthy debris; but the finding of glaciated pebbles in dredgings far south of all glaciers shows that bergs occasionally carry stones far from land. The importance of icebergs as agents of transportation has been greatly exaggerated, and the assignment of shoals, like the Banks of Newfoundland, to them, is without foundation.

*Map work.* See *Interpretation of Topographic Maps*, Exercises XI to XIII, and Plates XCV to CXXIX, Professional Paper 60, U. S. Geological Survey.

# CHAPTER VI

## THE WORK OF THE OCEAN

A few facts concerning the depth of the ocean and the distribution of its water have been given on a preceding page (p. 5), and reference to the origin of the ocean basins and the ocean will be made later. We are concerned here chiefly with the geologic processes now going on in the sea; but a few facts concerning the sea-water and its life, and the topography of the ocean's bed,[1] may well precede the study of the processes now in operation.

**Mineral matter in solution.** Every 1,000 pounds of sea-water contain about 34.40 pounds of mineral matter in solution. The principal substances in the water are the following:[2]

| | |
|---|---|
| Chloride of sodium | 77.758 |
| Chloride of magnesium | 10.878 |
| Sulphate of magnesium | 4.737 |
| Sulphate of calcium | 3.600 |
| Sulphate of potassium | 2.465 |
| Carbonate of calcium | 0.345 |
| Bromide of magnesium | 0.217 |

There are many other mineral substances in sea-water, and the gases oxygen, nitrogen, and carbon dioxide are present in quantity. The amount of the last is estimated to be 18 times that in the atmosphere.

The amount of sea-water is estimated at about 324,000,000 cubic miles, or about 15 times the volume of the land above sea-level. The volume and composition of the sea-water being known, the amount of its mineral matter may be calculated. Assuming the average specific gravity of the mineral matter to be 2.5, the 3.5% (nearly) by weight becomes about 1.4% by volume, and 1.4% of 324,000,000 cubic miles is 4,536,000 cubic miles. This represents approximately the volume which the mineral matter of the sea

[1] Much information on these and other points is to be found in the following books: Wild's *Thalassa;* Thompson's *Depths of the Sea;* Barker's *Deep Sea Soundings*, and Agassiz's *The Three Cruises of the Blake*. The *Challenger Reports* give more detailed information for certain regions.

[2] Dittmar, Challenger Reports, Physics and Chemistry, Vol. I, p. 204.

would have if it were precipitated and compacted so as to have an average specific gravity of 2.5. This amount of mineral matter would cover the ocean bottom to a depth of about 175 feet. Its amount is equal to about 20% of that of all lands above sea-level.

A large part of the mineral matter of the sea has come from the land, where it was dissolved chiefly by ground-water, and carried to the sea by rivers. But the mineral matter of the sea gives no more than a hint of the importance of the solvent work of water in the general processes of rock decay, for most of the mineral matter carried from the land to the sea in solution is taken from sea-water about as rapidly as it is received. Calcium carbonate, for example, is about twenty times as abundant as sodium chloride in river-water, but it is only 1/200 as abundant in sea-water. This is because the calcium carbonate is used by animals and plants to make shells, skeletons, etc., while the salt remains in solution.

From the amount of water discharged by rivers into the sea each year (about 6,500 cubic miles), and from the amount of salt it carries, it is calculated that it would take about 370,000,000 years for the salt of the sea to have been contributed by rivers, *at the present rate.* This figure, however, must not be taken as the age of the ocean, for (1) the salt is not all brought in by rivers, (2) it is not probable that the rivers have always contributed salt at the present rate, and (3) much salt once in the sea has been precipitated. Nevertheless the above figure gives some suggestion as to the order of magnitude of the figure which represents the age of the ocean.

**Topography of ocean basins.** The ocean basins are convex upward. It is only when we remember that a level surface (on the earth) is one which has the mean curvature of the earth, and that the deeper parts of the ocean basin are considerably below the mean sphere level, that the name basin seems appropriate.

The bed of the ocean, like the face of the land, has elevations and depressions, and its deepest parts are about as far below its surface as the highest mountains are above it. If the water were drawn off, so that the bottoms of the ocean basins could be seen, three great features would appear: (1) Extensive tracts of low land (now covered by deep water); (2) other great, but less extensive tracts of higher land (now covered by shallow water); and (3) ridges and peaks of mountainous heights. These three principal divisions may be compared to the plains, plateaus, and mountains of the land, though mountain systems would be less numerous than

on land. In addition there are great depressions comparable to the great basins of the land.

Apart from these general features, there is little in common between the topography of the sea bottom and that of the land. If the ocean's bed could be seen as the land is, its most impressive feature would be its monotony. The familiar hills and valleys which give the land its most familiar features are essentially absent. A large part of the ocean bottom is so nearly flat that the eye would not detect its departure from planeness.

The reason for this difference is readily found. The dominant processes which shape the details of the surface of the land are degradational, and though the final result of degradation is flatness (base-level), the earlier result is roughness. In the sea, the dominant processes are aggradational, and tend to planeness.

**Distribution of marine life.** Marine life has been of such importance in the history of the earth that the elementary facts concerning its distribution and the principles which control it are here recalled. Its distribution is influenced by many factors, chief among which are *temperature* and *depth of water*. It is more abundant in the warmer parts of the ocean than in the colder, the species inhabiting cold waters are different from those in warm, and few species range through great variations of temperature. Many forms are restricted to shallow water; many others, especially those living near the surface, swim about freely without reference to depth; while a few are restricted to great depths. Some species are influenced by (1) the *salinity of the water*, which varies considerably along coasts where the fresh waters from the land are discharged; (2) the *character of the sediment* at the bottom, some species preferring mud, others sand, etc.; (3) the *movement of the water*, some species preferring quiet water and others rough water; (4) the *abundance and nature of the food-supply;* and (5) the *presence or absence of rival and hostile species.*

Subject to exceptions determined by temperature, etc., plant life abounds in the superficial parts of the ocean, and down to the bottom where the depth does not exceed 100 fathoms. Animal life is abundant in shallow water at all depths down to 200 or 300 fathoms, and in the surface-waters of temperate and tropical regions regardless of depth. The great body of the ocean-water lying below the depth of a few hundred fathoms has but little life, though animals exists sparingly at the bottom, even where the depth is great.

### PROCESSES IN OPERATION IN THE SEA

**Diastrophism.** So far as the lithosphere is concerned, the sea-level is the *critical level.* At this level and above, many processes are in operation which are not effective below, while below sea-level some processes are effective which find no counterpart above. Warpings of the surface which do not involve the submergence of land or the emergence of sea bottom, are relatively unimportant compared with those which do. The rise of the bottom of the sea from a depth of 400 fathoms to a depth of 200 fathoms would not have important results, so far as the area itself is concerned, while an equal rise of the bottom beneath 100 fathoms of water, or an equal sinking of land 500 feet high, would be much more important.

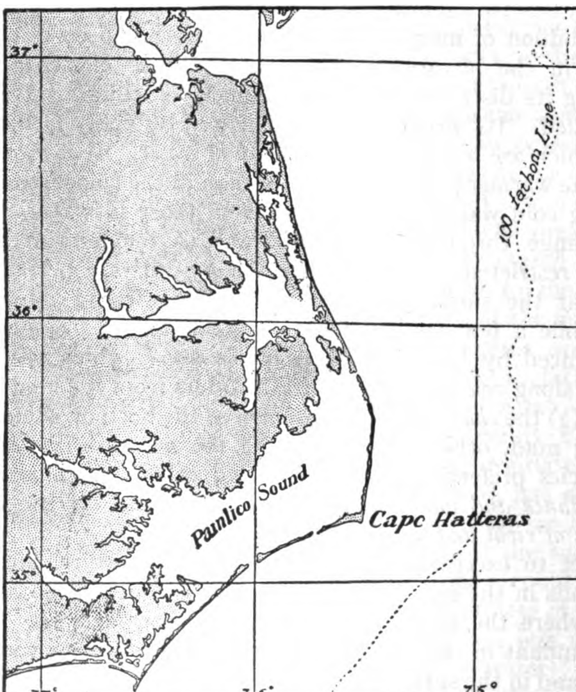



Fig. 174. Map showing the early stages in the simplification of a shoreline by deposition, and showing that at this stage the irregularities are increased. If the land rose or the sea sank 100 fathoms, the coast-line would be regular.

It follows that the changes effected by diastrophism are more obvious in shallow water than in deep. Emergence or submergence shifts the zone of contact of ocean and land, and so the areas of aggradation and degradation, and changes the region concerned from one appropriate for sea life to one appropriate for land life, or *vice versa*.

Over the continental shelves the water is shallow and the bottom relatively smooth. If the sea-level were drawn down, or if the continental shelf were elevated evenly, the new shore-line on the smooth surface of the former submerged shelf would be regular relatively, even though the coast was notably irregular before the change. This is illustrated by Fig. 174. Subsidence of a coast-line (or rise of the sea-level) tends to the opposite result, for in this case the sea advances on a surface which has relief, and the water covers every low place sunk to its level. Thus the numerous bays at the lower ends of the streams along the Atlantic coast from Long Island Sound to Carolina are the results of recent sinking. From the present configuration of coast-lines it has been inferred that the present is an era of continental depression. Some river valleys, the lower ends of which are embayed, are found to be continuous with

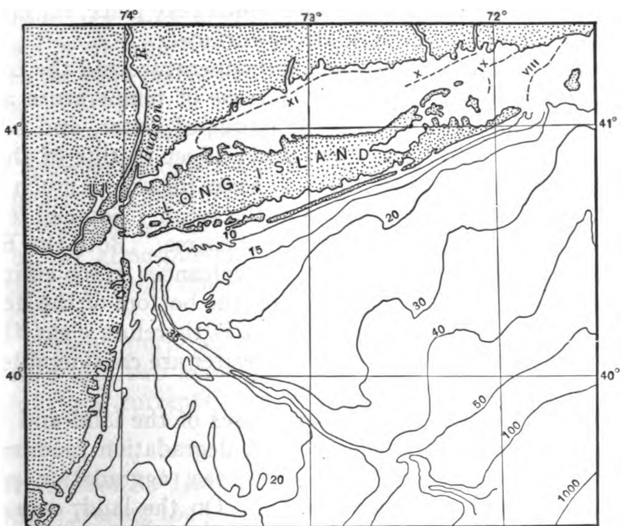



**Fig. 175.** The submerged valley which has been interpreted as the continuation of the Hudson Valley. The position of the valley is indicated by contours. (Data from C. and G. Survey.)

submerged valleys beyond the coast-line (Fig. 175). Submerged river valleys show that the surface in which they lie was once land.

The effects of diastrophism in the ocean and about its borders, may (1) make the water of any ocean, or of any part of it, shallower or deeper; (2) cause the emergence or submergence of land; (3) make coast-lines regular or irregular; (4) shift the habitat of many forms of life, and, through these changes, (5) influence the processes of gradation, especially at and near the contact of sea and land.

**Vulcanism.** Vulcanism affects the sea-bottom much as it affects land. At the volcanic centers, where the great body of extruded matter accumulates, mounds and mountains are built up, and most of the mountain peaks of the sea-bottom had a volcanic origin. Where volcanic cones are built up near the surface of the sea, they may furnish a home for shallow-water life, such as polyps. Wherever they are built up so as to be within the reach of waves, gradational processes are stimulated.

The number of active volcanoes on islands is about 200, but the number of active vents beneath the sea is unknown. A few submarine eruptions have been observed, but those observed are probably but a small percentage of those which take place, for eruptions in deep water may not be seen at the surface.

Oceanic volcanoes affect both the temperature and the composition of the sea-water. Both the increase of temperature and the volcanic gases increase the solvent power of water, and both the change in temperature and composition affect the life of the adjacent waters. Volcanoes in the sea have furnished much of the sediment now found on the bottom of the ocean. Some of it is very fine, like volcanic dust, and some of it is coarse. Both the fine and the coarse are distributed far from the volcanoes which emit them, are found indeed nearly everywhere on the bottom of the deep sea, though not in uniform abundance. It is therefore clear that the effects of oceanic volcanoes on the sea-water are considerable, when long periods of time are considered.

**Gradation.** The gradational processes of the land and the sea are in striking contrast. On the land, degradation predominates, and aggradation is subordinate; in the sea, aggradation predominates and degradation is subordinate. On the land, degradation is greatest, on the whole, where the land is highest, while aggradation is of consequence only where the land is low, or where steep slopes give place to gentle ones. In the sea, degradation is vir-

tually confined to shallow water, or to what might be called the highlands of the sea, while aggradation is nearly universal, though most considerable in shallow water, or where shallow water gives place to deep. Both the degradational and aggradational work of the sea are greatest near its shores. Though the gradational work on the land and in the sea are in strong contrast, they tend to a common end — the leveling of the surface of the lithosphere.

The gradational processes of the sea-bottom are effected (1) by mechanical, (2) chemical, and (3) organic agencies. *Mechanical* gradation is effected chiefly by the movements of the water. These may be degradational where the water is shallow enough for the motion to affect the bottom, but elsewhere they are aggradational. Gradation by *chemical* processes is likewise partly degradational and partly aggradational. In lagoons and other small inclosures, the water may become saturated with mineral matter; with further evaporation, precipitation takes place, the precipitate accumulating as sediment on the bottom. On the other hand, solution results in degradation. *Organic* agencies are, on the whole, aggradational. Accumulations of coral, coral debris, shells, etc., help to build up the sea-bottom. In the aggradation effected directly by organic agencies, the sea is passive. Its only part is to support the life which produces the solid matter, and incidentally to float a part of it in its currents.

## MOVEMENTS OF SEA-WATER

The movements of sea-water fall into several categories. There is (1) a general circulation of sea-water, determined by (a) differences in density in the sea-water, (b) differences of level, and (c) movements of the atmosphere; (2) periodic tidal movements; and (3) aperiodic movements due to earthquakes, volcanic explosions, landslides, etc.

For present purposes, all movements of the sea-water may be grouped into two main classes — (1) waves, with the undertow and the littoral currents they generate, and (2) ocean-currents.

### *Waves*

**Wave-motion.**[1] The most common waves are those generated by winds. During the passage of a wave, each particle affected by

[1] In the following pages concerning the waves and their work, Gilbert's discussion of shore features, in the Fifth Annual Report of the U. S. Geol. Survey, pp. 80–100, is freely drawn on. See also Fenneman, Jour. of Geol., Vol. X, pp. 1–32.

it rises and falls and moves forward and backward, describing an orbit in a vertical plane. If the passing wave is a swell, the orbit of the particle is a circle or an ellipse; but in the case of a wind-wave the orbit is not closed, for in such a wave the water, as well as the undulation, moves forward. On the crest of the wind-wave each particle of water moves forward, and in the trough it moves less rapidly backward, and the excess of the forward movement over the backward gives the water a slight advance. As a result of this advance, the upper part of the water is carried forward with reference to that below, in the direction toward which the wind blows. The waves of any considerable or long-continued wind, therefore, generate a surface movement in the direction of the wind.

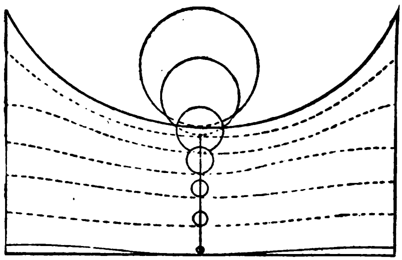


Fig. 176. Diagram illustrating the decreasing size of orbits of water particles in a wave, with increasing depth.

Wave motion is propagated downward indefinitely, but the amount of motion diminishes rapidly with increasing depth (Fig. 176). Engineering operations have shown that submarine structures are little disturbed at depths of five meters in the Mediterranean, and eight meters in the Atlantic. On the other hand, debris as coarse as gravel, which is transported by rolling on the bottom, may be carried out to depths of 50 feet, and sometimes even to 150 feet. Fine sediment, like silt, is disturbed at still greater depths, for ripple-marks, which indicate agitation of the water, are said to have been found at depths of 100 fathoms.

When a wave approaches a shelving shore, its habit is changed. The velocity of the undulation is diminished, while the velocity of the advancing particle of water in the crest is increased; the wave-length, measured from trough to trough, is diminished, and the wave-height is increased; the crest becomes acute, with the front steeper than the back, and these changes culminate in the breaking of the crest when the undulation proper ceases. Waves of a given height break in about the same depth of water, and the line along which incoming waves break is the *line of breakers*. The line of breakers is in deepest water and farthest from shore when the waves are strongest. The return of the water thrown forward

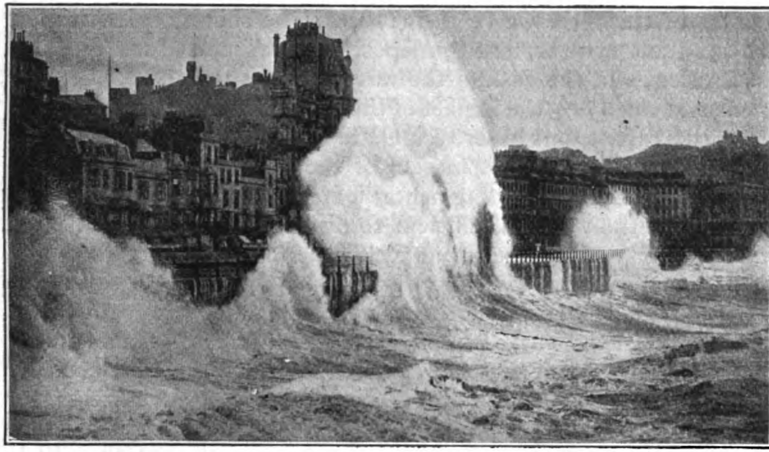


Fig. 177. Shore wave breaking on east wall of Hastings. (From Wheeler's *The Sea Coast;* by permission of Longmans, Green and Company.)

in the crests of waves is accomplished by a current along the bottom, called the *undertow*, which is sensibly normal to the coast when uninfluenced by oblique waves.

When waves advance on shore obliquely, a shore-current is developed as illustrated by Fig. 178, where *ab* represents the direction of the incoming wave, *bc* the direction of the shore (or *littoral*) current, and *bd* the direction of the undertow. Where they strike the borders of land, the wind-waves, therefore, generate two other movements, the undertow and the littoral current. Any particle of water near shore may be affected by any two or by all three of these movements at the same moment. The effect of littoral current and undertow is to give a particle of water on which both are working a direction between the two, as *be*. The effect of other combinations is readily inferred. These various combinations are of consequence in the transportation of debris. Waves and the move-

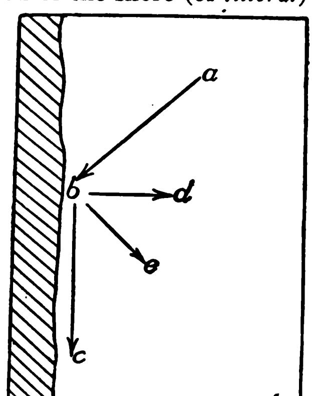



Fig. 178. Diagram showing relative directions of wave, undertow, and shore-current.

ments to which they give rise (1) wear the shores, (2) transport the products of wear, and (3) deposit the transported materials.

**Erosion.** In the dash of the waves against the shore, the wear is effected chiefly by the impact of the water and of the debris which the water carries, but lesser results are accomplished in other ways.

When the land at the margin of the water consists of unconsolidated material, or of fragmental material but slightly cemented, the dash of the water is sufficient to displace or erode it. If weak rock is associated with resistant rock within the zone of wave-work, the removal of the former may lead to the disruption and fall of the latter, especially when weak rock is washed out from beneath strong. The impact of the water is competent also to break up and remove rock which was once resistant, but which has been weakened by weathering. Rock affected by joints is attacked with success, for the blocks bounded by joints may be loosened and quarried out. Waves of clear water, even when their force is very great, have little effect on rock which is thoroughly solid.

The effect of the impact of the waves is generally increased by the detritus they carry. The sand, the pebbles, and such stones

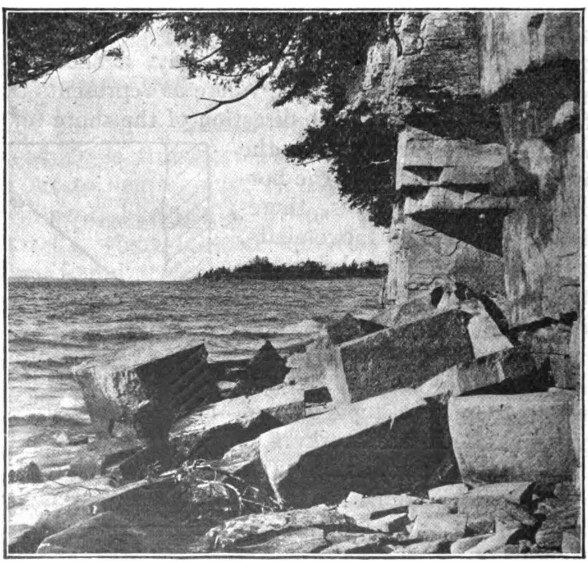


Fig. 179. Angular blocks of rock, fallen from the cliff above, as a result of undercutting by waves; Grand Island, Lake Champlain.

as the waves can move are used as weapons of attack, both against the shore and against one another. Masses of rock too large for the waves to move (Fig. 179) are worn by the detritus driven back and forth over them, and in time reduced to movable dimensions. They then become the tools of the waves, and, in use, are reduced still more. Thus bowlders are worn to cobbles, cobbles to pebbles, pebbles to sand, and sand to silt. The silt, held in suspension in agitated water, is carried out beyond the range of breakers, and

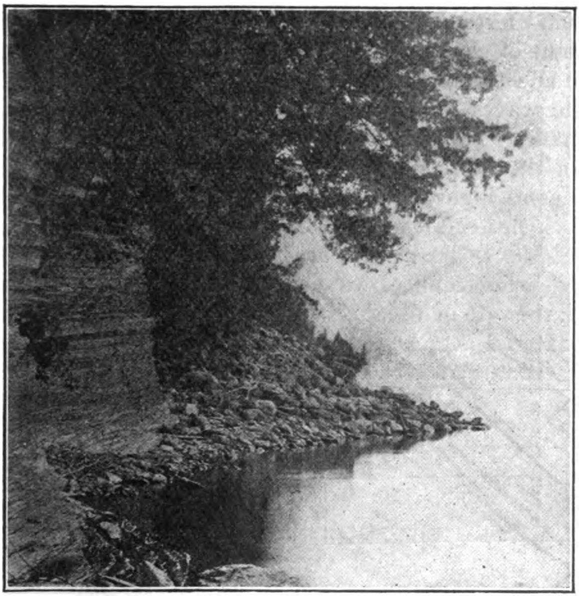


Fig. 180. Showing blocks similar to those of Fig. 179, but reduced and rounded by wave-action. Shore of Lake Champlain. (Perry.)

settles in water so deep as not to be agitated to its bottom. Thus one generation of shore bowlders after another is worn out, and the comminuted products come to rest in deeper water.

The effectiveness of waves depends on their strength and on the concentration of their blows.[1] The average force of waves on the Atlantic coast of Britain has been found to be 611 lbs. per square foot in summer, and 2,086 lbs. in winter, but winter breakers which

[1] Willis, Jour. of Geol., Vol. I, p. 481.

exert a pressure of three tons per square foot are not infrequent. Exceptional storm-waves have moved blocks of rock exceeding 100 tons in weight. Waves are most efficient on bold coasts bordered by broad expanses of deep water, for here their force is expended almost wholly near the water line; where shallow water borders the land, the force of the waves is expended over a greater area.

The *direct effect* of wave-erosion is restricted to a zone which is narrow both horizontally and vertically. There is no impact of breakers at levels lower than the troughs of the waves, though erosion may extend down to the limit of effective agitation. The upper limit of effective wave-action is the level of the wave-crests. The rise and fall of the water during the flow and ebb of the tides gives the waves a greater vertical range than wind-waves alone would have. The *indirect work* of waves is limited only by the height of the shore, for as the zone of excavation is carried landward, masses higher up the slope are undermined and fall. The fallen rock protects the shore against the waves temporarily (Fig. 179), but the fallen masses are themselves broken up eventually.

The general result of wave-erosion is the advance of the sea on the land, the rate of advance being determined chiefly by the nature of the material attacked and the strength of the waves. Though examples of the retreat of coast-lines before the advance of the

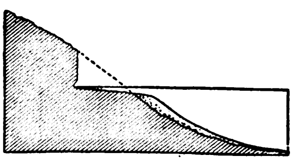


Fig. 181

Fig. 182

Fig. 181. High sea cliffs, and a submerged terrace, due partly to wave-cutting and partly to building.
Fig. 182. A low sea cliff.

sea are numerous, the advance is not universal or uninterrupted. On the contrary, the land encroaches on the sea in some places, and the two things may go on side by side. At Long Branch, N. J., advance of the sea has been so rapid in recent times as to menace important buildings, while a few miles to north and south, land is advancing into the sea by the deposition of shore drift. The low coast of the Middle Netherlands has retreated two miles or more in historic times, but the land has advanced at other points in the

same region. On the coast of England the sites of villages have disappeared by the advance of the sea within historic times,[1] but the coast of the same island affords illustrations of land advance. On the south side of Nantucket Island, the sea-cliff has been known to retreat before the waves six feet in a single year.[2] Almost every considerable stretch of coast affords illustrations both of the advance of sea on land and of land on sea; but in the long run, the former exceeds the latter.

**Topographic features developed by wave-erosion.** As the waves cut into the shore at and near the water-level, they develop a steep slope above the line of cutting. This steep slope is *the sea-cliff* (Figs. 181 to 184). The term *lake cliff* is applied to the corresponding cliffs of lakes.

The height of the cliff depends on the height of the land along shore. Its slope may be steep or gentle (Figs. 181 and 182). Rapid

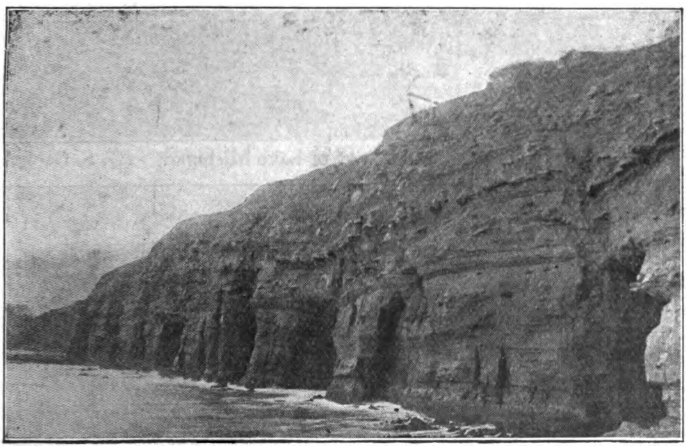


Fig. 183. A high sea cliff without a beach, La Jolla, Cal.

cutting and resistant material tend to produce steep cliffs; but steep cliffs may develop in incoherent materials, such as sand and clay, if cutting is rapid. The structure of the cliff-rock also influences the slope and configuration of the sea-cliff. By working in along the joints of the rock, widening them and quarrying out the intervening blocks, pillars of rock ("*chimney-rocks*," "*pulpit-*

[1] Dana, Manual of Geology, 4th ed., p. 219.
[2] Shaler, Sea and Land, p. 29.

*rocks*"), or even considerable islets are sometimes isolated by the waves (Fig. 185).

Waves may excavate *caves* at the bases of cliffs. The bottoms

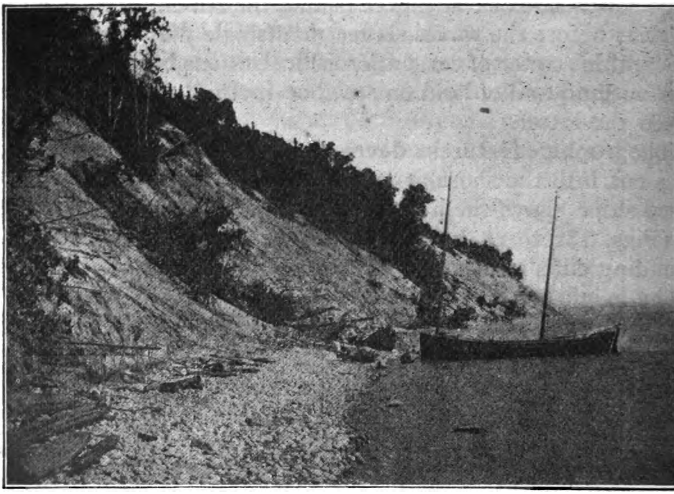


Fig. 184. High cliff, with beach; shore of Lake Michigan. (U. S. Geol. Surv.)

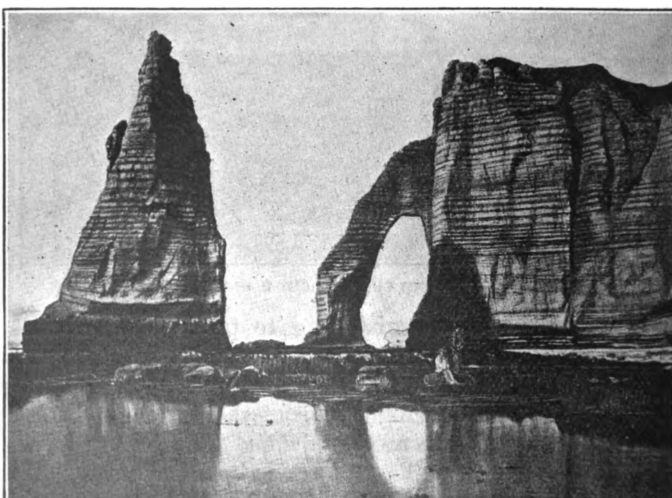


Fig. 185. A chimney rock and an arch on the coast of France. (Neurdein.)

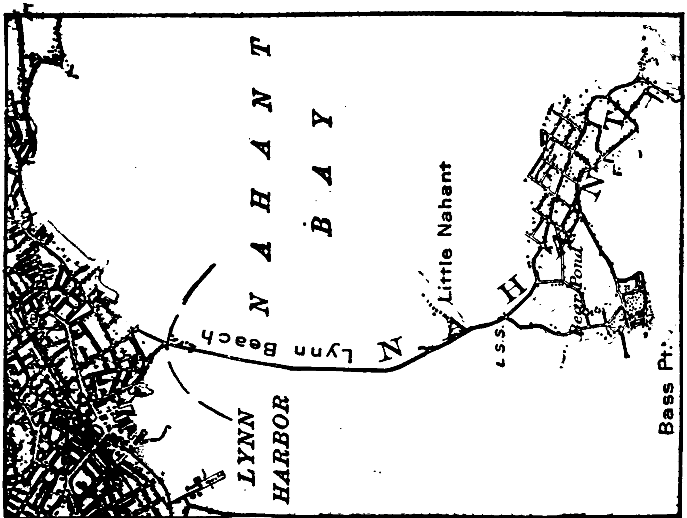



FIG. 1.—An island tied to the mainland by a "beach." Scale, about 1 mile per inch. Contour interval, 20 feet. (Boston Bay, Mass., Sheet, U. S. Geol. Surv.)

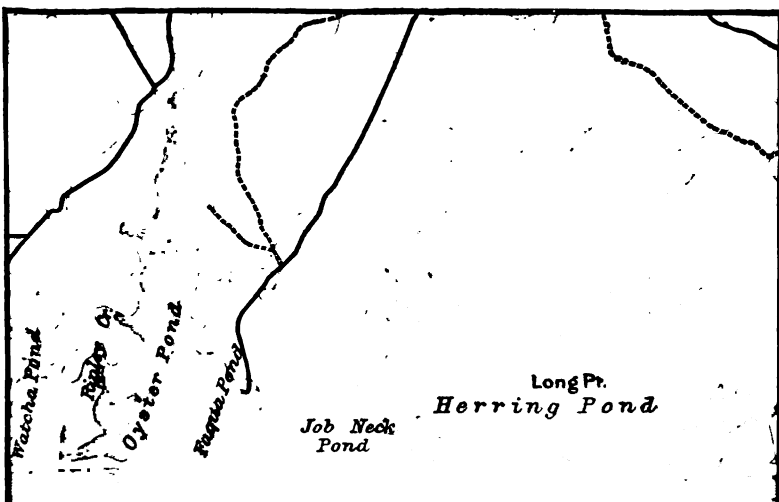
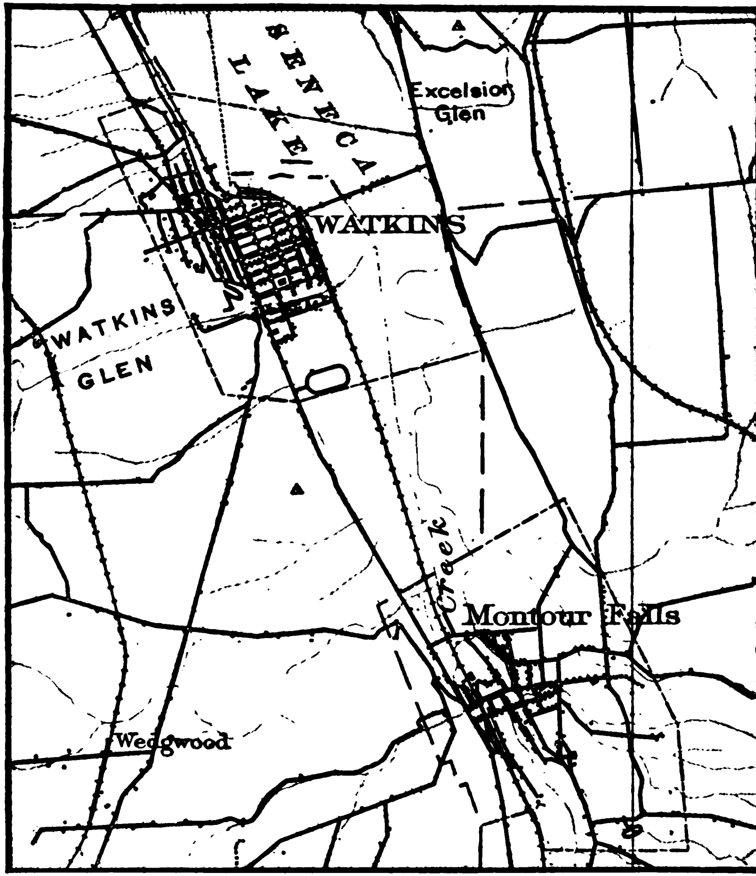



FIG. 2.—Coastal lakes formed by the blocking of the ends of drowned valleys. Scale, about 1 mile per inch. Contour interval, 20 feet. (Marthas Vineyard, Mass., Sheet, U. S. Geol. Surv.)

PLATE XVI




The upper end of Seneca Lake, New York. The flat between Montour Falls and Watkins is a delta which has been built out into the lake by the in-flowing creek. Scale, about 1 mile per inch. Contour interval, 20 feet. (Watkins, N. Y., Sheet, U. S. Geol. Surv.)

and roofs of most sea-caves have a pronounced inclination landward, and if the cliff is low, the cave may be extended landward until its roof is pierced. Through such an opening in the top of the cliff the water of the incoming waves may be forced in the form of spray. On the New England coast, such holes are sometimes known as "spouting horns." Similar openings may be made by the compression or rarefaction of the air in the cave as the wave enters or retreats. Sea caves, "spouting horns," "pulpit-rocks," and other isolated islets, all are closely associated with the sea-cliff in origin.

The bottom of the sea-cliff is bordered by a submerged platform over which the water is shallow. This platform, or at any rate its

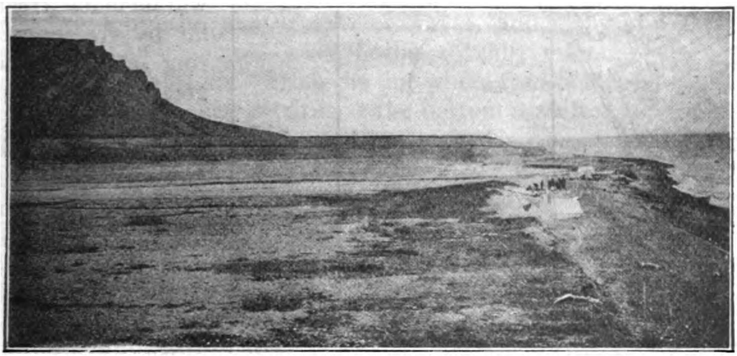


Fig. 186. Wave-cut terrace. The land has risen or the sea sunk since the terrace was cut. Seward Peninsula, Alaska. (U. S. Geol. Surv.)

landward portion, represents the area over which the water has advanced as the result of wave-cutting, and is known as the *wave-cut terrace*. Such a terrace is the necessary accompaniment of the cliff. Wave-cut terraces may become land by elevation, or by the lowering of the level of the sea (Fig. 186). Elevated sea-cliffs with wave-cut terraces at their bases are among the best evidences of change of relative level between water and land.

**Wave-erosion and horizontal configuration.** The structure of the rock along shore has much to do with the horizontal configuration of the wave-shaped coast. Wave erosion develops re-entrants in the weaker portions of the shore, leaving the more resistant parts as headlands (Fig. 2, Pl. VI. p. 69). It is to be noted that the resistance of rock to wave-erosion is not determined by its hardness alone.

Every division plane, whether due to bedding, to jointing, or to irregular fracture, is a source of weakness, and rock of great hardness may be so broken as to offer little resistance. A coast which is regular and of equal exposure, but of unequally resistant material, will be made irregular by wave-erosion. A regular coast of uniform material, but unequal exposure, will be made irregular by greater cutting at points of greater exposure. A coast of marked irregularity and homogeneous material will be made more regular by the cutting off of the projecting points, because they are most exposed. With a given set of conditions, waves tend to develop a certain sort of shore-line which, so far as its horizontal form is concerned, is relatively stable. Such a shore-line may be said to be *mature*[1] so far as wave-erosion is concerned. Since coastal lands are, in general, both heterogeneous and unequally exposed, a mature coast-line is somewhat irregular.

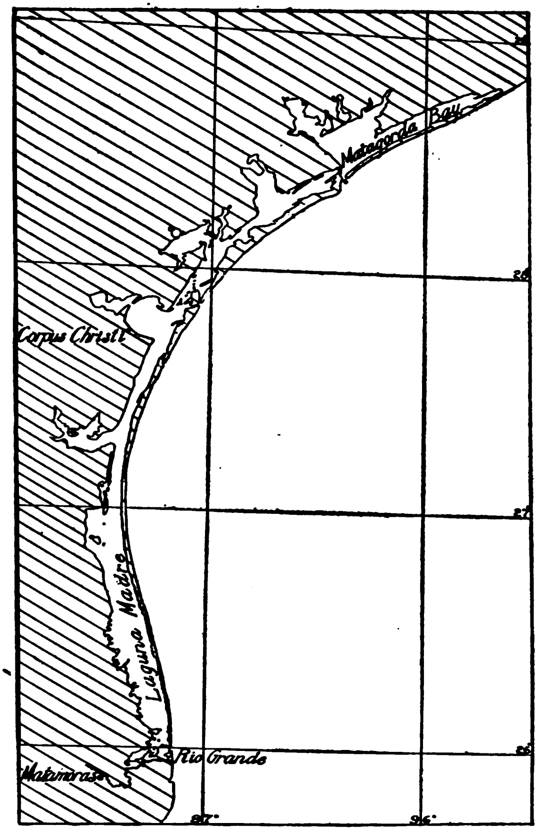



Fig. 187. Portion of the Texas coast, showing tendency of shore-deposition to simplify the coast line. The deposits (narrow necks of land parallel to the coast) shut in bays. (From chart of C. and G. Surv.)

[1] Gulliver, Shore Line Topography; Proc. Am. Acad. Arts and Sci., Vol XXXIV, 1899, pp. 151–258. A valuable study of shore-line topography.

Since the conditions of erosion along coasts are constantly, even if slowly, changing, maturity is constantly being approached, but rarely reached. Other forces and processes, such as those of aggradation, vulcanism, and diastrophism, are in operation along coasts, and their results may antagonize the waves. The horizontal configuration of coasts is, therefore, the result of many co-operating forces, of which waves are but one. It is, nevertheless, important to note the end toward which waves are working, even though they are continually defeated in their attempt to reach it. Their immediate goal is maturity of configuration; their final goal is the destruction of the land and the deposition of its substance in the sea.

**Transportation.** Material eroded from the shore by waves is transported by the joint action of waves, undertow, and shore-currents. The incoming wave begins to shift material where it begins to drag bottom. From the line where transportation begins, to the line of breakers, detritus at the bottom is shifted toward the shore by the waves, while the undertow tends to carry it back again. The result of these opposed movements is to keep sediment moving to and from the shore in shallow water. Waves which come in at right angles to the shore, and the undertow resulting, do not move sediment along the shore; but oblique waves and littoral currents do. The direction in which debris is shifted by waves and shore-current is modified by the undertow, and the direction which would result from undertow and current is modified by the wave (Fig. 178). Waves of storms, rather than those of prevailing winds, determine the direction of greatest transportation.

Waves, undertow, and littoral currents work together in assorting the detritus of the shore. If the coarsest parts are beyond the power of all but the strongest waves, they accumulate where agitation is great. Less coarse parts are carried farther from the site of greatest agitation, but no materials which are classed as coarse are carried beyond the depth of sensible movement. The coarse materials which cover the bottom where agitation of the water at the bottom is effective, and which are shifted about by waves, etc., constitute *shore drift*. The material which is fine enough to be held in suspension is measurably independent of depth. This is shown during storms when the water becomes turbid far beyond the zone of shore drift, and clears only after the waves have died away.

The sorting of shore drift, effected while it is in transportation, may be very perfect. The conditions favoring assortment are (1) vigorous wave-action, (2) prolonged transportation, and (3) a moderate volume of sediment.

**Deposition by waves, undertow, and shore-currents.** The zone occupied by shore drift in transit is the *beach*. Its lower margin is beneath the water, a little beyond the line where the great storm-waves break. Its upper margin is at the level reached by storm-waves, and is usually a few feet above the level of still water. Material is brought to the beach from seaward by incoming waves, and from it detritus is carried out by the undertow. The cross-section of a beach is shown in Fig. 188. The beach follows the general boundary between water and land, though it does not conform to its minor irregularities (Figs. 174 and 187). The beach (or barrier) may deflect the lower courses of streams descending to it.

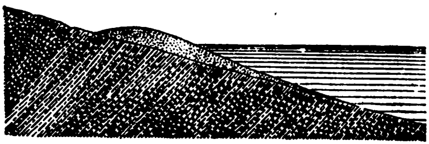


Fig. 188. Cross-section of a beach. (Gilbert.)

In its deposition, shore drift assumes various forms. Where the bottom near shore has a very gentle inclination, the incoming waves break some distance from the shore-line, and it is here that the most violent agitation occurs when the waves are strong. To this line of breakers, material is shifted from both directions. Accumulating here, it builds up a low ridge, called the *barrier* (Fig. 189). If it is built up above the surface of the water by storm-waves, it may shut in a lagoon behind it, and this may be filled ultimately by sediment washed down from the land. At one stage in the filling, the lagoon becomes a marsh (Fig. 191).

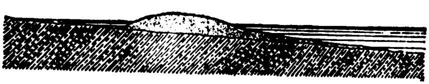


Fig. 189. Section of a barrier. (Gilbert.)

The disposition of shore deposits depends largely on the currents at and near shore. If the coast-line is deeply indented, the littoral current usually fails to follow the re-entrants. In holding its course across the mouth of a small bay, the velocity of the shore-current is checked because it passes into deeper water. Deposition follows. The deposits are in a narrow belt which marks the course of the current, and the result is the construction of a ridge beneath the water. The current does not build the embankment up to the

Fig. 190. An elevated barrier beach on the coast of California.

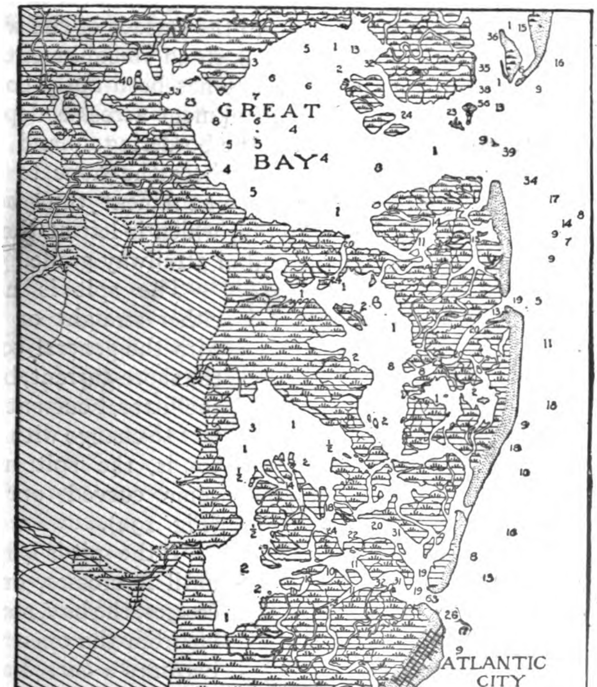



Fig. 191. Sketch-map of a part of the New Jersey coast. The dotted belt at the east is the barrier, modified by the wind. The area marked by diagonal lines is the mainland; the intervening tract is marsh-land. The numbers show the depth of water in feet. Scale: ¼ inch = 1 mile.

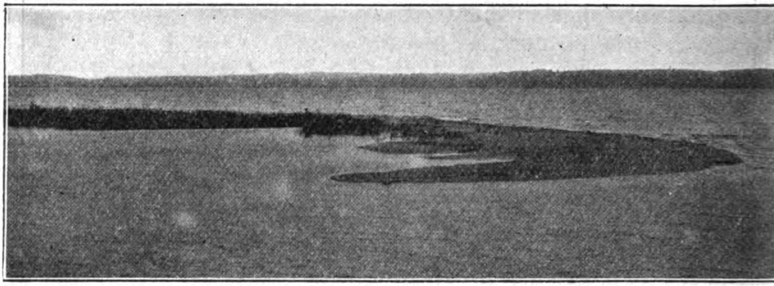


Fig. 192. A recurved spit, Dutch Point, Grand Traverse Bay, Lake Michigan. (U. S. Geol. Surv.)

water-level; but when its surface approaches the level of effective agitation, the waves may build it up to the surface of the water, or even above it. So long as the end of such an embankment is free, it is a *spit*. The construction of a spit has been aptly compared to the construction of a railway embankment across a depression. The material is first carried out from the bordering upland (in this case the shallow water) and dumped where the slope to the depression (deep water) begins. The embankment thus begun is extended by carrying out new material, which is left at the end of the dump already made, as at the end of a railway grade.


Fig. 193. Map of the head of Lake Superior. (U. S. Geol. Surv.)

The spit is normally either straight or parallel with the general course of the shore-current, but since the littoral current is subject to change with shifting winds, the spit may become curved or hooked (Fig. 192).

If the spit is lengthened until it crosses, or nearly crosses, the bay, shutting it off from the open water it becomes a *bar*. Bars have shut in lakes, ponds, and lagoons at numerous points both on the Atlantic and the Pacific coasts

(Pl. XV, Fig. 4 and Fig. 187). The same phenomena are to be seen along many lakes (Fig. 193). Bars may tie islands to the mainland (Pl. XV, Fig. 3). If the bay across which the bar is built receives abundant drainage from the land, the outflow from the bay may be sufficient to prevent the completion of the bar, for when the growth of the bar has narrowed the outlet of the bay sufficiently, the sediment brought to the end of the spit by the littoral current will be swept out by the current setting out from the bay. The completion of a bar may be interfered with also by tidal currents, even without land-drainage. The scour of the tides preserves deep entrances (inlets) to bays in some places, and maintains definite channels or "thorofares" in the lagoon marshes behind barriers and spits (Fig. 191). The sediment brought down from the land, as well as that washed in by tidal currents and waves, tends to fill up the lagoon behind a barrier, a spit, or a bar, converting it into land (Fig. 191).

Since spits and bars are built only where there is shore-drift in transit, they are always built out from a beach or barrier. The distal end of the bar also may join a beach or barrier. Traced back to its source, the beach from which a spit leads is in many cases found to end at the cliff from which the material of the beach and spit were derived.

The off-shore movements of shore-waters may leave the sediment of the shore in the form of a *wave-built terrace*, which is really a seaward extension of the beach. A wave-built terrace borders many wave-cut terraces along their seaward margins (Fig. 181). Terrace-cutting and terrace-building are both involved in the development of continental shelves.

Beach ridges, spits, bars, etc., like sea-cliffs and wave-cut terraces, are preserved for a time after the relative levels of sea and land have changed. If the shore has risen, relatively or absolutely, these features are evidence of the change. If shore features are submerged instead of elevated, they furnish less accessible though not less real evidence of the change. Similar features about lakes have a like significance, but there it is demonstrable, in many cases, that it is the water rather than the land which has changed level.

**Shore-deposition and coastal configuration.** The tendency of shore-deposition is to cut off bays and to straighten and simplify the shore-lines. This is abundantly illustrated along the Atlantic

and Gulf coasts of the United States (Figs. 174, 187, and Pl. XV, Fig. 1). It is to be noted, however, that in the simplification of the shore-line through deposition, the initial stages may result in great irregularity (Figs. 187 and 191).

### *Ocean-currents*

Ocean-currents are due primarily to winds. As agents of erosion, they are not of great importance. Currents which reach the bottom are comparable, in their effects, to rivers of the same velocity and volume; but most ocean-currents do not touch bottom, and therefore do not erode it. Only where they flow through narrow and shallow passageways is their abrasive work considerable. Thus the Gulf Stream has a velocity of four or five miles per hour where it issues from the Gulf, and its shallow and narrow channel is current-swept. Other illustrations of the erosive power of currents have been noted near Gibraltar in water 500 fathoms deep, and between the Canary Islands at depths of 1000 fathoms. In spite of such examples, it yet remains true that ocean-currents are on the whole but feeble agents of erosion. They are scarcely more important in transporting, for they carry little except that which they erode, if the life which lives in them is disregarded. Currents which do not touch bottom roll no sediment, and carry only what is held in suspension. A river's power of transporting sediment in suspension is due largely to cross-currents occasioned by the unevenness of its resistant bottom. If a particle of mud suspended in a river drops to the bottom, as it frequently does, it may be picked up again and carried forward. If, on the other hand, a particle suspended in an ocean-current once escapes the moving water by settling through it, the current which does not drag bottom has no chance to pick it up again. Very fine sediment may be carried by an ocean-current far from the point where it was acquired, but currents which do not touch bottom are rarely strong enough to carry any but the finest material.

How readily particles of extreme fineness may be kept in suspension, and how little agitation is necessary to keep them from sinking, is shown both by experiment and observation. Experiment has shown that fine particles of clay require days to settle a foot in still water, and the Challenger found fine sediment derived from the land 400 miles from the coast of Africa. Sediment settles more readily in salt water than in fresh, despite the fact that the

former is heavier. This is presumably because the salt diminishes the cohesion of water.

### DEPOSITS ON THE OCEAN-BED

The deposits on the bed of the ocean may be divided into two classes[1]— *shallow-water deposits*, made in water less than about 100 fathoms deep, and *deep-sea deposits*, laid down in water of greater depth. The selection of the 100-fathom line as the dividing depth is less arbitrary than it seems, for passing outward from the shore, it is at about this depth that the bottom ceases to be commonly disturbed by the action of currents and waves; that sunlight and vegetable life cease to be important at the bottom; and that the coarser sediments which predominate along shore give place to muds and oozes. Furthermore, the 100-fathom line (or some line near it) is an important one in the physical relief of the globe, for it appears to mark, approximately, the junction of continental plateaus and ocean-basins. Because the latter are a little overfull, the water runs over their rims, covering about 10,000,000 square miles of the borders of the continental protuberances.

Aside from the deposits made by organisms, shallow-water deposits are divisible into two groups — (1) those immediately along the shore, the *littoral deposits*, and (2) those between the littoral zone and the 100-fathom line. Both are terrigenous chiefly, though chemical and organic deposits occur in both. The deep-sea deposits likewise are divisible into two principal groups, (1) the *terrigenous deposits* near the land, and (2) the *pelagic deposits*, made chiefly of the remains of pelagic organisms, and the decomposed products of such other materials as reach the deep sea.

#### *Shallow-water Deposits*

**Littoral deposits.** The littoral zone is often defined as the zone between high- and low-water marks, but in common speech, the very shallow water a little farther from the coast-line is generally included. It is the zone in which sand and coarser materials accumulate, though muds are met with occasionally in sheltered estuaries. Generally speaking, the nature of these deposits is determined by the character of the adjoining lands and the local organisms. The heavier materials brought down by rivers or worn from the shore by waves are here spread out by waves and shore-currents.

[1] Murray, Challenger Report, Deep Sea Deposits, pp. 184, 185.

Twice in twenty-four hours the littoral zone is covered by water, and twice parts of it are exposed to the direct rays of the sun or the cooling effects of the night. Physical conditions in general are here most varied. Still greater diversity is introduced by the fact that the zone is inhabited by both marine and terrestrial organisms, while the evaporation of the sea-water which flows over tidal marshes and lagoons leads to the formation of saline deposits. The length of the coast-lines of the world is some 125,000 miles (about 200,000 kilometers), so that the zone of littoral deposits, though narrow, covers a very considerable area.

**Extra-littoral deposits.** These deposits are made between the littoral zone and the 100-fathom line, and cover an area of nearly 10,000,000 square miles. Their composition is much the same as that of the littoral deposits except that they are finer. At their lower limit they pass insensibly into the fine deposits of the deep sea. Coarse materials, such as gravel and sand, prevail, though in depressions and inclosed basins, and out toward the oceanward edge of the zone, muddy deposits are found. Some of the deposits are composed wholly of inorganic debris, but organic remains are mingled freely with others. The mechanical effects of tides, currents, and waves are everywhere present, but become less and less well marked as the 100-fathom line is approached. The forms of

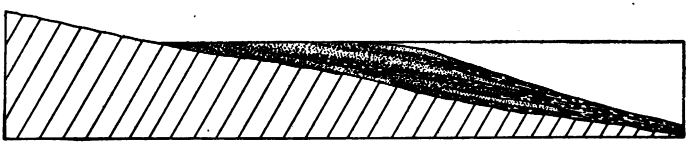


Fig. 194. Diagram showing the interwedging of gravel, sand, and mud beds.

vegetable and animal life are numerous, though the former decrease as depths which make the sunlight feeble are approached.

No definite line marks the seaward terminus of the coarse detritus, since coarse material is carried farther out when the waves run high (and the undertow is strong) than when they are feeble. In calm weather fine sediment may be deposited where coarse was laid down in the preceding storm, to be covered in turn by deposits of a different character. Thus gravel grades into sand, with more or less overlapping or interwedging, and sand grades into silt in the same way. This is diagrammatically illustrated by Fig. 194.

Since coarse deposits may extend far out from land where the waves are strong and the water shallow, and since the zone of shallow water may be extended seaward by the aggradation of the bottom, shallow-water deposits may cover extensive areas. They may

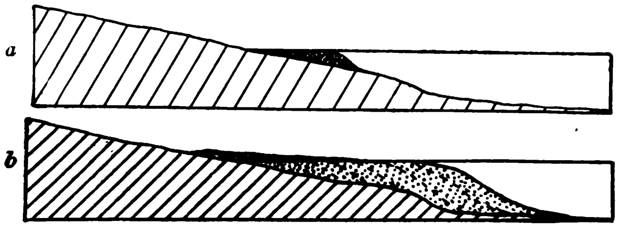



Fig. 195. Diagrams showing how shallow-water deposits may attain considerable thickness by the shifting of the zone of deposition seaward.

become deep at the same time, for as the outer border of the shallow-water zone is shifted seaward by aggradation, the vertical space to be filled becomes greater (compare *a* and *b*, Fig. 195). Again, if the coast is sinking, new deposits of coarse material may be made on older ones. In this way, also, great thicknesses of sediment may

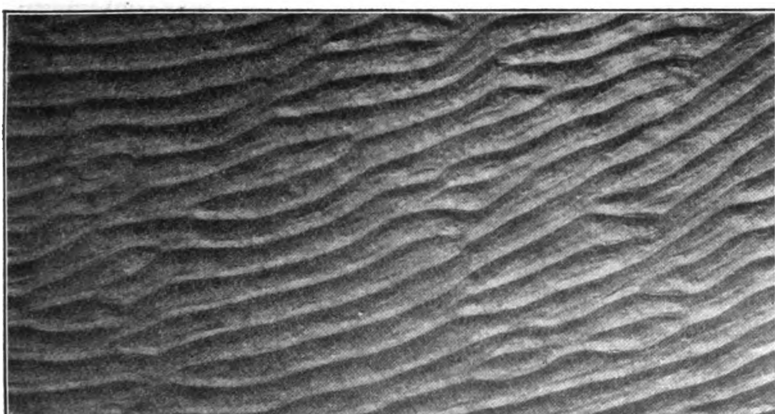


Fig. 196. Ripple-marks.

be accumulated, all parts of which were deposited in shallow water. The great thicknesses of some of the conglomerate beds of the past show how far this may go.

**Characteristics of shallow-water deposits.** Clastic sediments laid down in shallow water have several distinctive characteristics. While they are coarse as a whole, they are characterized by many variations in coarseness. The surfaces of successive beds are likely to be ripple- and rill-marked (Figs. 196 and 197), and cross-bedding (Figs. 198 and 199) is common. Clayey sediments deposited between high and low water may be sun-cracked (Figs. 200 and 201), and the tracks of land animals are in some cases preserved on their surfaces. Shallow-water deposits may contain fossils of organisms which live in waters of slight depth. These characteristics differentiate sedimentary formations made in shallow water from those made in deep water, even after they have been converted into solid rock, and after the rock has emerged from the sea. Many of these characteristics are, however, shared by deposits made by streams on land. Subaërial and lacustrine sediments are distinguishable from those made in the sea by their fossils, their distribution, etc.

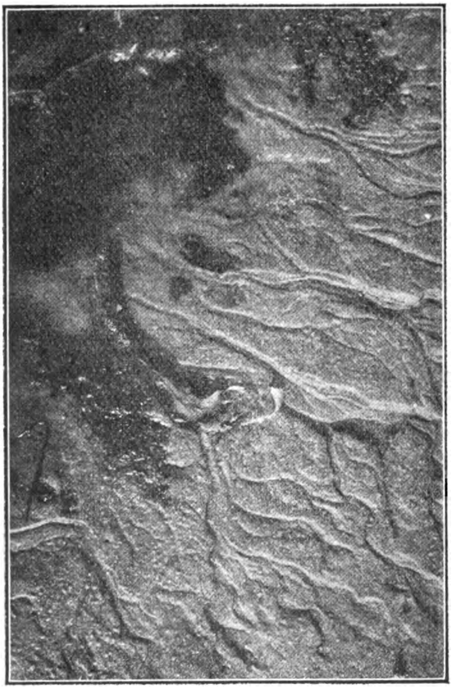


Fig. 197. Rill-marks resembling impressions of seaweeds. Beach at Noyes Point, R. I. (Walcott, U. S. Geol. Surv.)

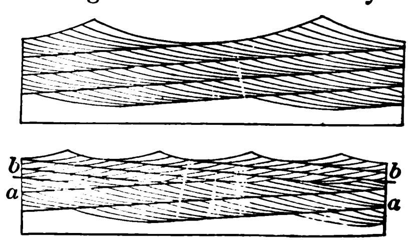



Fig. 198. Cross-bedding. (Gilbert.)

Shallow-water deposits have, on the whole, a rather

plane surface, though there are some notable departures from flatness. The steep slopes of the delta fronts and of wave-built terraces have already been noted (pp. 187, 191). Barriers may shut in depressions, and the disposition of sediment may be uneven, owing to shore and tidal currents. The result is that the surfaces of shallow-water deposits are affected by low swells and shallow sags. The swells and sags may be elongate, circular, or irregular in outline. This topography is in some cases preserved on newly emerged lands.

**Chemical and organic deposits in shallow water.** There is no sharp line of distinction between the deposits classed as chemical and those classed as organic. The latter are chemical in the broader

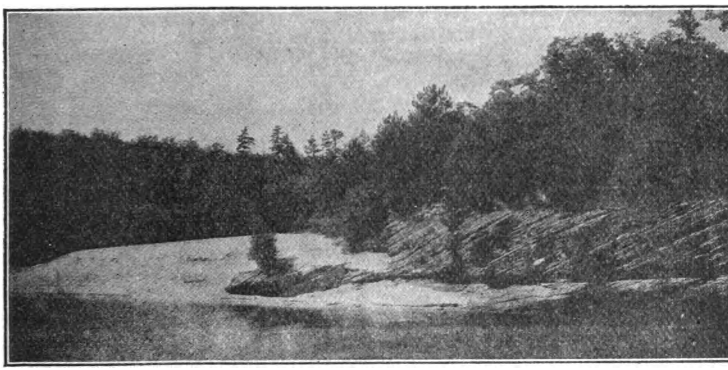


Fig. 199. Cross-bedded sandstone, Dells of the Wisconsin. The strata are horizontal. The laminæ within each stratum dip notably. (Atwood.)

sense of the term, but as they are directly associated with life and arise from it, it is a matter of convenience to separate them. Chemical deposits made in shallow sea-water embrace (1) those due to evaporation, and (2) those due to chemical reactions between constituents so brought together that new and insoluble compounds are formed and precipitated.

The chemical deposits made in the shallow water of the sea, or in bodies of shallow water isolated from the sea, are chiefly precipitates resulting from evaporation. All substances in solution are necessarily precipitated on complete evaporation; but since the sea-water is in general far from saturation, so far as all its leading salts are concerned, only a few are thrown down in quantity sufficient to be of geologic importance where evaporation is incomplete.

The principal deposits of this sort are calcium carbonate (limestone, $CaCO_3$) calcium sulphate (gypsum, $CaSO_4,2H_2O$), common salt (rock salt, NaCl), and magnesium salts, chiefly the chloride and sulphate.

While there is more than ten times as much lime sulphate as lime carbonate in the ocean (p. 167), deposits of the carbonate (including shells, coral, etc.) have been very much greater than those of the sulphate. This is due to the following facts: (1) The

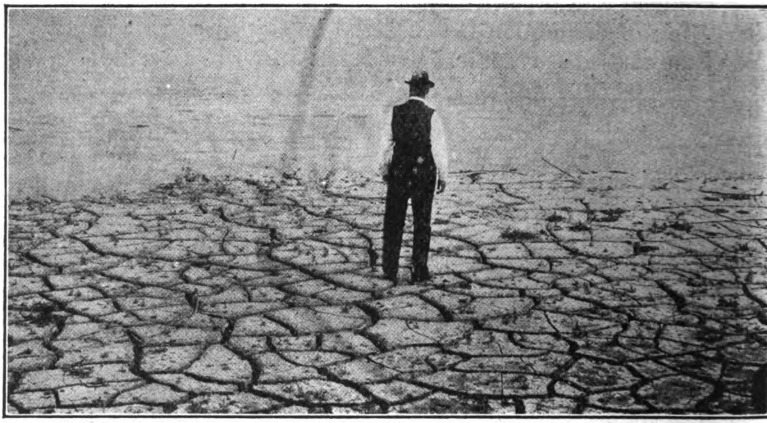


Fig. 200. Sun-cracks; flat of the Missouri a few miles above Kansas City. The sun-cracks on shore deposits are not essentially different. (Calvin.)

sulphate is much more soluble than the carbonate, (2) rivers bring much more carbonate than sulphate to the sea, and (3) marine plants and animals extract the carbonate from the water for their skeletons, shells, etc. The secretion of lime carbonate by organisms is not dependent on the saturation of the water, but is carried on when the amount in solution is very small.

The chief deposits of *lime carbonate* have been made through the agency of plants and animals, in the form of shells, coral, bones, and other devices for supporting, housing, protecting, and arming themselves; but while it is agreed that the larger part of the lime carbonate deposited in the open sea is of organic origin, it is equally clear that in closed seas subject to concentration from evaporation, direct precipitation may take place. There is difference of opinion as to the quantitative importance of this last class of deposits.

*Gypsum* appears to be deposited in quantity only in the basins of arid regions where concentration reaches an advanced state. Since normal sea-water is far from being saturated with *common salt*, the latter is precipitated only in lagoons, in closed seas, or other situations favorable to great concentration. This is, as a rule, only in regions which are notably arid. It follows that deposits of salt usually signify highly arid conditions, and where they occur

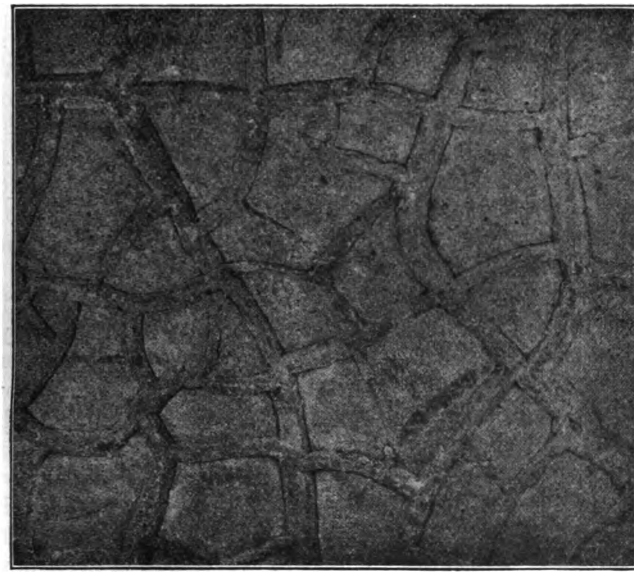


Fig. 201. **Records of sun-cracks in sandstone. About three-eighths natural size.** (Geikie.)

over wide ranges in latitude and longitude, as in certain periods of the past, general aridity of climate is inferred. Where confined to limited areas, their climatic significance is less, for topographic conditions may determine local aridity. The total area where salt is now being precipitated is small, though on the whole the present is probably a rather arid period of the earth's history. On the other hand, ancient deposits of salt preserved in the sedimentary strata show that the area of salt deposition has been much more considerable than now at one time and another in the earth's history. The salt and gypsum deposits of the past seem, therefore, to tell an interesting tale of the climates of bygone days.

The *magnesium salts* are among the last to be thrown down as sea-water is evaporated, and they most commonly take the form of sulphates and chlorides. The magnesium salts are among the last to be precipitated, not only because they are readily soluble, but because their quantity is small; yet in the original rock from which the sea-salts came, there is at least as much magnesium as sodium, while in the sea there is about five times as much sodium as magnesium. Just what becomes of all the magnesium brought to the sea-water is not well understood. In the older marine strata, *dolomite*, composed partly or wholly of the double carbonate of lime and magnesia $(CaMg)CO_3$, abounds. This appears to have been formed by a gradual substitution of magnesium for calcium in calcium carbonate, but just how and when and why the substitution was effected is not fully known. One view is that dolomite was formed chiefly in basins not freely connected with the sea.

The plants and animals of the sea secrete notable quantities of silica, but deposits of this sort are relatively more important in the deep sea, and will be mentioned in that connection.

Something concerning the origin of limestone has already been given in the preceding paragraphs; but because of the importance of this rock, it may be added, by way of summary, that shallow seas free or nearly free from terrigenous sediment, and abounding in lime-secreting life, furnish the conditions for nearly pure deposits of limestone, and that most of the limestone within the areas of the present continents appears to have originated under such conditions. The common notion that limestone is normally a deep-water formation is an error. Although limestones are formed in deep as well as in shallow waters, the more important classes of lime-secreting organisms are limited to the depths to which light penetrates. After being formed, limestones may lose many of their original characteristics, but enough usually remain to tell the story of their origin.

### *Deep-sea Deposits*

**Contrasted with shallow-water deposits.** Deep-sea deposits cover the ocean-bottom below the 100-fathom mark. Their area is about two-thirds of the earth's surface. The characteristic deposits are muds, organic oozes, and clays, which, in their physical characteristics, are remarkably uniform. In regions of floating ice, some diversity is introduced from the varied nature of the materials which it transports.

The slow accumulation of sediment on the deep-sea bottom, the absence of transportation there, and the nature and small size of the particles, all favor chemical reactions which result in the formation of many new products, such as glauconite, phosphatic and manganic nodules, zeolites,[1] etc. The amount of matter arising from the decomposition and alteration of minerals and rocks increases, relatively, with increase of distance from the land. At the same time there is an increase (relative), in all moderate depths, of the remains of pelagic organisms. We thus pass insensibly from deep-sea deposits of a terrestrial origin (*terrigenous deposits*) near the land, to *pelagic deposits*, "in which the remains of calcareous and siliceous organisms, clays, and other substances of secondary origin play the principal role."[2]

The following table[3] shows the relations of the various groups of marine deposits.

| | | |
|---|---|---|
| 1. Deep-sea deposits beyond 100 fathoms | Red clay<br>Radiolarian ooze<br>Diatom ooze<br>Globigerina ooze<br>Pteropod ooze | I. Pelagic deposits formed in deep water far removed from land |
| | Blue mud<br>Red mud<br>Green mud<br>Volcanic mud<br>Coral mud | II. Terrigenous deposits formed in deep and shallow water, mostly close to land |
| 2. Shallow-water deposits between low-water mark and 100 fathoms | Sands, gravels, muds, etc. | |
| 3. Littoral deposits between high- and low-water marks | Sands, gravels, muds, etc. | |

In spite of this classification of Murray, the coral and volcanic muds cannot be regarded as terrigenous, and shells, coral, etc., are found abundantly in shallow-water deposits. It is to be noted that the pelagic deposits are partly organic and partly inorganic in origin. The latter may be of mechanical or chemical origin.

**Mechanical inorganic deposits.** The mechanical deposits of the deep sea come from (1) the land by the ordinary processes of gradation, (2) volcanic vents, and (3) extra-terrestrial sources. The terrigenous materials which reach the deep sea are, as a rule, only

[1] "The generic name for a group of hydrated double silicates in which the the principal bases are aluminum, and calcium or sodium."

[2] Murray, Challenger Rept., Deep Sea Deposits.

[3] Ibid., p. 186.

the finest products of land decay, carried out by movements of water and by winds. They are not commonly recognized in the dredgings more than 200 miles from shore, but opposite the mouths of great rivers they extend much farther — 1,000 miles in the case of the Amazon. They are especially abundant on the slopes of the continental shelves, where the *blue*, *green*, and *red muds* are associated with volcanic and coral muds. The color of these various muds depends in part at least on the changes they have undergone since their deposition. These deposits are analogous, in a general way, to certain shales, marls, etc., found on the continents.

The occasional presence of coarse materials from the land in the deep-sea deposits must be looked upon as in some sense accidental. Pebbles, or even bowlders, entangled in the roots of floating trees, may be carried out into the ocean, and icebergs carry out bowlders and smaller fragments of rock. Of the identifiable inorganic materials in the pelagic deposits, those of volcanic origin are most abundant. Their distribution is essentially universal, though not uniform. Some of them are probably from submarine volcanoes.

Deep-sea deposits contain many nodules and grains believed to be of extra-terrestrial origin. The dust of the countless meteors which enter the atmosphere daily settles on land and sea alike, and must enter into the sediment at the bottom of the latter. It is probably no more abundant in deep water than in shallow, but it is relatively more important, since there is little other sediment. The number of meteorites which enter the atmosphere daily has been estimated at from 15,000,000 to 20,000,000.[1] If, on the average, they weigh ten grains each, probably a rather high estimate, the total amount of extra-terrestrial matter reaching the earth yearly would be 5,000 to 7,000 tons, and something like three-fourths of this must, on the average, fall into the sea. But even at this rate it would take some fifty billion years to cover the sea-bottom with a layer one foot in thickness.

**Organic constituents of pelagic deposits.** With increasing distance from shore, and especially with increasing depth of water, sediments derived from pelagic life increase in relative importance. Some pelagic animals and plants secrete lime carbonate, while diatoms and radiolarians secrete silica. When the organisms die,

[1] Young's Astronomy, p. 472. It is now believed that these figures are too small.

they sink to the bottom and their secretions are mingled with the volcanic and other materials which are universal over the sea-floor.

Pelagic deposits of organic origin are named according to their characteristic constituents. Thus there are *pteropod oozes*, *globigerina oozes*, *diatom oozes*, *radiolarian oozes*, etc. Diatom ooze is an ooze in which the secretions of diatoms are abundant, and globigerina ooze is an ooze in which globigerina shells are abundant, though in many cases the diatom and globigerina shells, respectively, do not make up the bulk of the ooze. Between the various sorts of oozes there are all gradations, since pelagic life does not recognize boundary lines.

It is a significant fact that with increasing depth the proportion of lime carbonate in the ooze decreases. Thus in tropical regions remote from land, where the depth is less than 600 fathoms, the carbonate of lime of the shells of pelagic organisms may constitute 80% or 90% of a deposit. With the same surface conditions, but with increasing depth, the percentage of lime carbonate decreases, until at 2,000 fathoms it is less than 60%; at 2,400 fathoms, 30%, and at 2,600 fathoms, 10%. Beyond this depth there are usually no more than traces of carbonate of lime. The data at hand show that the percentage of lime carbonate falls off below 2,200 fathoms more rapidly than at lesser depths. Where the percentage of lime carbonate becomes very low, the calcareous oozes grade off into the *red clay* with which the sea-floor below 2,400 to 2,600 fathoms is covered.

**Chemical deposits.** The chemical deposits of the deep sea are chiefly the alteration products of sediments which reach the sea-bottom by mechanical means. All sediment deposited in the sea undergoes more or less chemical change, but it is only when the change is very considerable that the product is referred to this class. Where sedimentation is rapid and the sediment coarse, the chemical change is relatively slight; but where the sedimentation is slow and the sediment fine, the chemical change is relatively great; for both the longer exposure to the sea-water and the greater proportion of surface exposed to attack favor change. The *red clay* already referred to belongs to this class of deposits. It contains much volcanic debris,[1] various concretions, bones of mammals, zeolitic crystals, and extra-terrestrial spherules, and doubtless the

[1] Murray, Challenger Report on Deep Sea Deposits, p. 337 et seq., and Buchanan, Proc. Roy. Soc. Edin., Vol. XVIII, pp. 17–39.

insoluble parts of the shells of pelagic life. The nodules and crystals are secondary products, the materials for which were derived from the decomposition of the sediments which gave rise to the clay. Eolian dust, or the materials derived from it by chemical alteration, is doubtless a constituent of the red clay.

It is significant that deposits corresponding to those of the deep sea have not been identified with certainty among the rock formations of the land. If such deposits are absent from the land, as they seem to be, their absence must mean that the continents have never been beneath *deep seas*. That large parts of them have been beneath shallow sea-water is abundantly attested.

*Map work.* See Plates CXXX–CLIV, Professional Paper 60, U. S. Geological Survey, and Laboratory Manual, *The Interpretation of Topographic Maps*, Exercise XV.

# CHAPTER VII

## LAKES

Many of the phenomena of the ocean are repeated on a smaller scale in lakes. The waves of lakes and their attendant undertows and littoral currents are governed by the same laws and do the same sort of work as the corresponding movements of the ocean. Tides are insignificant; but slight oscillations of level, known as *seiches*, have been observed in many lakes. They are probably caused by sudden changes in atmospheric pressure. Currents corresponding to those of the ocean are slight or wanting in lakes, but since most lakes have inlets and outlets, their waters are in constant movement toward the latter. In most cases this movement is too slow to be noted readily, or to do effective work either in corrasion or transportation. The work of ice is relatively more important in lakes than in the sea.

**Changes taking place in lakes.** The processes in operation in lakes are easily observed and readily understood. (1) The waves wear the shores, and the material thus derived is transported, assorted, and deposited as in the sea, and all the topographic forms resulting from erosion or deposition along the seacoast are reproduced on their appropriate scale in lakes. (2) Streams bear their burden of gravel, sand, and mud into lakes and leave it there. (3) The winds blow dust and sand into them, and in some places pile the sand up into dunes along their shores. (4) Animals of various sorts live in lakes, and their shells and bones give rise to deposits comparable to animal deposits in the sea. (5) Numerous plants grow in the shallow water about the borders of many ponds and lakes, and as they die, their substance accumulates on the bottom. (6) The outlets of lakes which have outlets are constantly lowered by the outflow. The lowering is generally slow if the rock is coherent, for the outflowing water is usually clear, and therefore inefficient in corrasive work. These six processes (except the last, which does not apply to lakes without outlets) are essentially universal, and all conspire against the perpetuity of the lakes. (7) In lakes where the

temperature is low enough for ice to be formed, it crowds on the shores and develops phenomena peculiar to itself (Figs. 126–127). (8) In some lakes in arid regions, deposits are made by precipitation from solution.

Several of these processes are filling the basins of lakes, and as sediment is deposited in a lake, a corresponding volume of water is forced out if the lake has an outlet. The sixth process also is antagonistic to lakes. Given time enough, these processes must bring the history of any lake to an end. The lowering of the outlet alone will accomplish this result if the bottom of the basin is above base-level. Many lakes already have become extinct, either through the filling or draining of their basins, or through both combined. It does not follow, however, that lakes will ever cease to exist, for the causes which produce them may operate contemporaneously with those which tend to destroy lakes now in existence.

**Lacustrine deposits.** Beds of sediment deposited in lakes are similar in kind, structure, and disposition, to beds of sediment laid down in the sea; but in lakes river-borne sediment is more commonly concentrated into deltas, since waves, tides, and shore-currents are less effective than in the sea. Even the limestone of the sea has its counterpart in some lakes. Some of it was made of the shells of fresh-water animals which throve where the in-wash of terrigenous sediment was slight, some of it from the calcareous secretions of plants,[1] and some of it was precipitated from solution.[2] While still soft, such deposits are called *marl*. Salt deposits also are made in some lakes, and iron-ore in some marshy ones.

**Extinct lakes.** The former presence of lakes where none now exist is known in various ways. If a lake basin was filled, its former area is a flat, the material of which bears evidence of its origin in its composition, its structure, and in its fossils. Such a flat commonly is so situated topographically that the basin would be reproduced if the deposits were removed. To this general rule there are exceptions, as where a glacier formed one side of the basin when it was filled. If the lake was destroyed by the lowering of its outlet, or by the removal of some barrier such as glacier ice, or by desiccation, shore phenomena, such as beaches, terraces (Fig. 202), spits, etc., may exist, even though there is no well developed flat

[1] C. A. Davis, Jour. of Geol., Vol. VIII and Vol. IX.

[2] Russell, Mono. XI, U. S. Geol. Surv., Chap. V; also Third Ann. Rept., pp. 211–221. Gilbert, Mono. I, U. S. Geol. Surv., p. 167.

corresponding to the bed of the lake. In time, such features are destroyed by subaërial erosion, so that they are most distinct soon after a lake disappears.

Many lakes, some of them large and many of them small, are known to have become extinct,[1] while many others are now in their

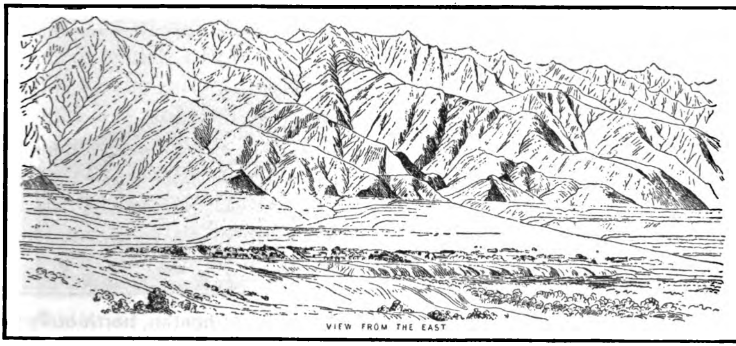



Fig. 202. Shore terraces of extinct Lake Bonneville, Wellsville, Utah. (Thompson and Holmes.)

last stages, viz., marshes. Many others have been reduced in size. Such reductions are obvious where deltas are built into lakes. Thus the delta built by the Rhone into Lake Geneva is several miles in length, and has been lengthened nearly two miles since the time of the Roman occupation. The end of Seneca (N. Y.) Lake (Pl. XVI) has been crowded northward some two miles by deposition at its head. Similar changes are common.

**Salt lakes.** A few lakes, especially in arid or semi-arid regions, are salt, and others are "bitter." Beside common salt, most salt lakes contain magnesium chloride, and magnesium and calcium sulphates, as well as other mineral substances. Most "bitter" lakes contain sodium carbonate, as well as sodium chloride and sulphate, and some of them borax. The degrees of saltness and bitterness range up to saturation. The water of the Caspian Sea (lake) contains, on the average, less mineral matter than that of

[1] Gilbert, Lake Bonneville, Mono. I, U. S. Geol. Surv.; Russell, Lake Lahontan, Mono. XI, U. S. Geol. Surv.; and Mono Lake, Eighth Ann. Rept., U. S. Geol. Surv., Pt. I; Upham, Lake Agassiz, Mono. XXV, U. S. Geol. Surv.; Salisbury and Kümmel, Lake Passaic, Rept. of the State Geologist of N. J. 1893, and Jour. of Geol., Vol. III, pp. 533–560.

the sea; that of Great Salt Lake contains about 18%; that of the Dead Sea, about 24%.

Many salt lakes, such as Dead Sea and Great Salt Lake, are

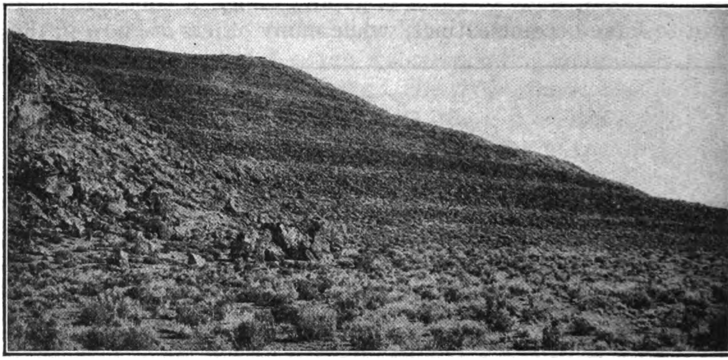


Fig. 203. Terraces on the shore of the ancient Lake Lahontan, north of Pyramid Lake, Nevada. (Fairbanks.)

descended from lakes which were fresh, while others, like the Caspian Sea, are probably isolated portions of the ocean. Most lakes of the former class have become salt through a decrease in the

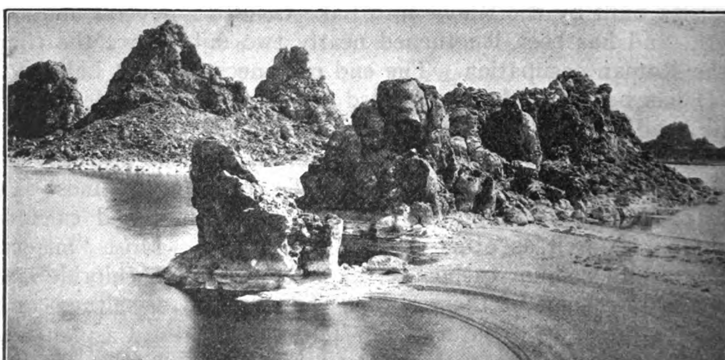


Fig. 204. Tufa domes, Pyramid Lake, Nevada. (Fairbanks.)

humidity of the region where they occur. The inflowing waters bring in small amounts of saline matter, and the water begins to be salty when the aridity is such that evaporation from the lake

exceeds its inflow. Under these conditions concentration may go on to saturation.

Deposits of salt and other mineral matters are now making in some salt lakes, and formations of the same sort have been made in the past. Buried beneath sediments of other sorts, beds of salt or other precipitates are preserved for ages. Lime carbonate has been precipitated in quantity from some extinct lakes (Fig. 204).

Lakes which originate by the isolation of portions of the sea are salt at the outset. If inflow exceeds evaporation, they become less and less salty, and may become fresh ultimately; otherwise they remain salt. If evaporation exceeds inflow they diminish in size and their waters become more and more salt or bitter.

**Indirect effects of lakes.** Lakes tend to modify the climate of the region where they occur, both by increasing its humidity and by decreasing its range of temperature. They act as reservoirs for surface-waters, and so tend to restrain floods and to promote regularity of stream flow. They purify the waters which enter them by allowing their sediments to settle, and so influence the work and the life of the waters below.

**Origin of lake basins.**[1] Lake basins arise in many ways, some of which have been pointed out. Most of them arise through processes of gradation. Some are formed by rivers (p. 114), some by waves and shore-currents (p. 186), and some by glacial erosion and deposition. Others are formed by volcanic action, as we shall see, and some by warpings of the earth's surface. A few originate in other ways.

[1] Salisbury's Physiography, Advanced Course, p. 303.

# CHAPTER VIII

## THE MOVEMENTS AND DEFORMATIONS OF THE EARTH'S BODY (DIASTROPHISM)

The outer parts of the lithosphere are subject to a variety of movements, some rapid and some slow, some slight and some great, some limited to small areas, some affecting extensive tracts, and some involving the whole earth. For present purposes, they may be classed as (1) small and rapid, and (2) great and slow. Sudden movements of local masses, such as avalanches and landslides, are put in the first class.

### MINUTE AND RAPID (SEISMIC [1]) MOVEMENTS

The crust of the earth is in a state of perpetual tremor. For the most part, these tremors are too slight to be sensible, though detected by delicate instruments. Some of them precede or follow earthquake vibrations, but more of them have no connection with violent movements. Many spring from the ordinary incidents of the surface, such as waves, waterfalls, winds, tides, the tread of animals, the rumble of traffic, and the blasting in mines. Movements due to such causes demonstrate the elastic nature of the crust, but are not considered here.

### *Earthquakes* [2]

Earthquakes are tremors of appreciable violence springing from sources within the earth. The causes are various. The most common is probably the slipping of rock masses on each other in the process of faulting (Chapter X). To the same class belong movements due to slumping, which is superficial faulting. Tremors

[1] The science of earthquakes is *Seismology*. Earthquakes and other similar movements are *seismic* movements. The instruments which record seismic movements are seismographs, etc.

[2] Recent and instructive books on Earthquakes are Dutton's *Earthquakes;* Hobbs's *Earthquakes. An Introduction to Seismic Geology;* Milne's *Earthquakes* (4th ed.), and the same author's *Seismology;* and Knott's *Physics of Earthquake Phenomena.*

attend many volcanic eruptions, and are attributable to the sudden fracture and displacement of rock by the movements of lava, or by the expansion due to heating. Quakes have also been attributed to the sudden generation or cooling of steam in underground conduits, crevices, and caverns, and to the collapse of the roofs of subterranean caves.

**Points of origin; foci.** It is probable that nearly all earthquakes start within ten miles of the surface, and most of them within five.

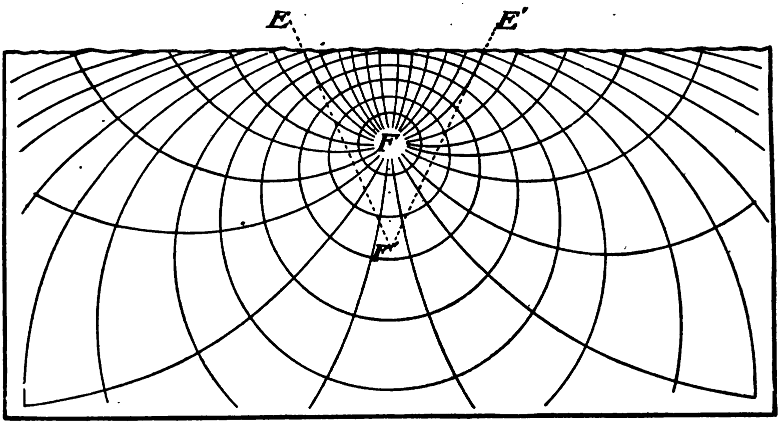



Fig. 205. Diagram illustrating by closed curves the different rates of propagation of seismic tremors from a focus *F*, and, by lines normal to these, the changing directions of propagation of the wave-front. Propagation is least rapid toward the surface where rocks are least elastic. The paths of propagation curve upwards in approaching the surface. If the lines of emergence, as at *E* and *E′*, are projected downward in straight lines to *F′*, the point of crossing will be below the true focus. The line at the top of the Fig. represents the surface of the earth.

The older calculations which placed some of the foci much deeper, appear to be defective.

The depth of the sources of disturbance is usually estimated by noting the directions in which bodies at the surface are thrust during an earthquake, plotting these directions, and projecting them backwards to their underground crossings (lines EF′ and E′ F′, Fig. 205). In the case illustrated by Fig. 205, this would place the focus at F′. This method gives only a rude first approximation to the location of the focus, which may be a point, a line, or a plane. The earthquake wave travels out from the focus with unequal velocity in various directions. This is because the rock varies in density, elasticity, temperature, etc. The aggregate effect of these variations is to make earthquake waves travel more slowly toward the surface than in other directions, and more and more slowly as the surface is approached. This is illustrated by Fig. 205, in which each closed curve connects

points reached by the wave at the same moment. The lines normal to these curves represent the directions in which the wave is propagated, in its various parts. The meeting point of these lines gives the true focus, F, which is much nearer the surface than F′.

**Amplitude of vibrations.** From the disastrous effects of earthquakes it might be inferred that the vibrations have large ampli-

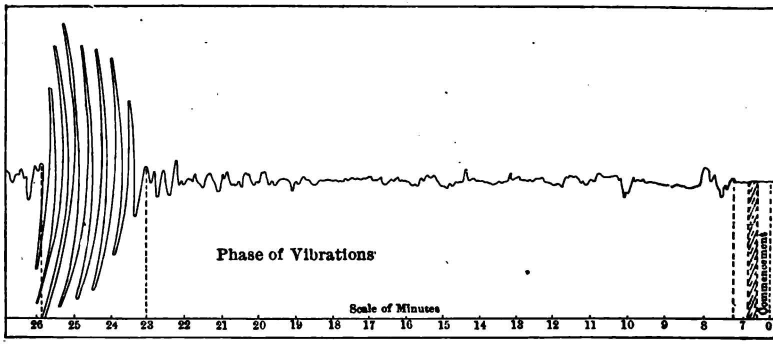



Fig. 206. Seismogram of earthquake in Punjab, India, April 4, 1905, showing the actual amount of movement. (Montessus de Ballore.)

tudes; but it is chiefly their suddenness that makes them effective. Except at their points of origin, most of them are only a fraction of a millimeter, and few exceed a few millimeters. It is the oscillation of the rock particles transmitting the vibrations that is here meant,

Fig. 207. A fissure on East Street, San Francisco, near the water front, in "made ground." (Lindgren, U. S. Geol. Surv.)

not the movement of objects on the surface, which may be much greater. A sudden shock with an amplitude of 5 or 6 millimeters is sufficient to shatter a chimney.

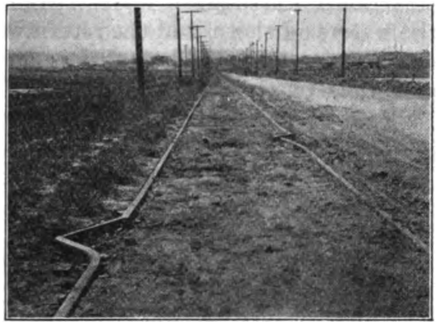


Fig. 208. Track of electric railway, between South San Francisco and San Bruno Point. (Photo. by Moran.)

**Destructive effects.** The disastrous effects of earthquake shocks result from (1) the suddenness and strength of rather small vibrations of earth-matter, and from (2) the freedom of motion of the bodies affected. The deeper rocks probably transmit seismic vibrations without appreciable disruptive effect; but bodies at the surface are broken, overturned, and displaced. The tap of a hammer sends an almost imperceptible vibration along the floor; but this vibration would throw a glass ball beneath which it runs considerably above the floor. Similarly the minute seismic vibrations

Fig. 209. Great sea-wave on the coast of Ceylon. (Sieberg.)

travel miles from their origin through continuous substance with little result, and yet may then hurl a loose or unstable body to destruction. Earthquake waves striking the sea-border may thrust the waters off shore, and the return wave may overwhelm the coast (Fig. 209). Sea-waves doubtless arise also from sudden seismic vibrations on the sea-bottom.

**Rate of propagation.** The progress of a seismic wave varies

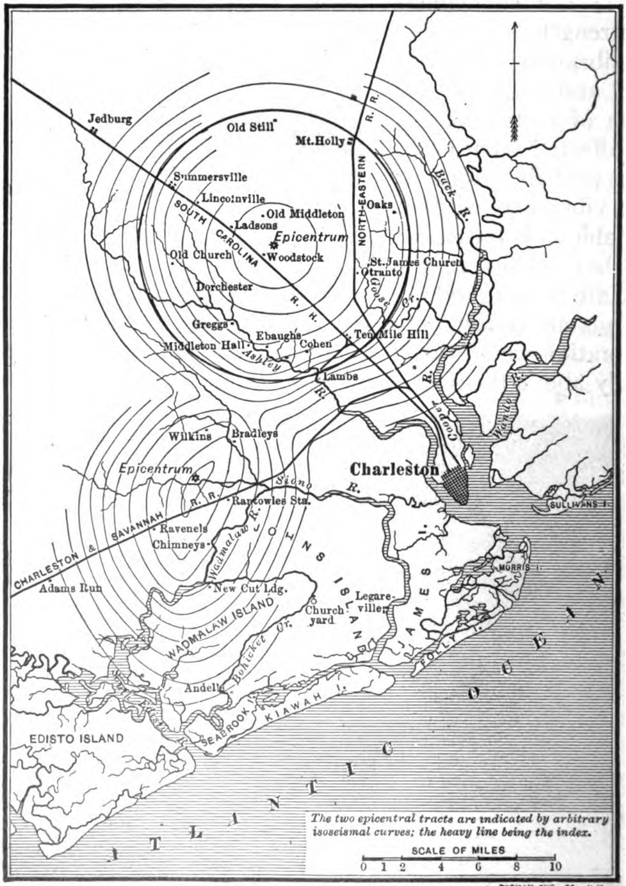



Fig. 210. Epicentral tracts of the Charleston earthquake, with isoseismal lines (lines of equal disturbance). (Dutton, U. S. Geol. Surv.)

appreciably. The violent vibrations on the surface near the epicentrum (point above the focus) are the most irregular, and strong vibrations generally have greater speed than weak ones. Vibrations propagated to great distances through and around the earth are less irregular in rate. Those which follow the surface

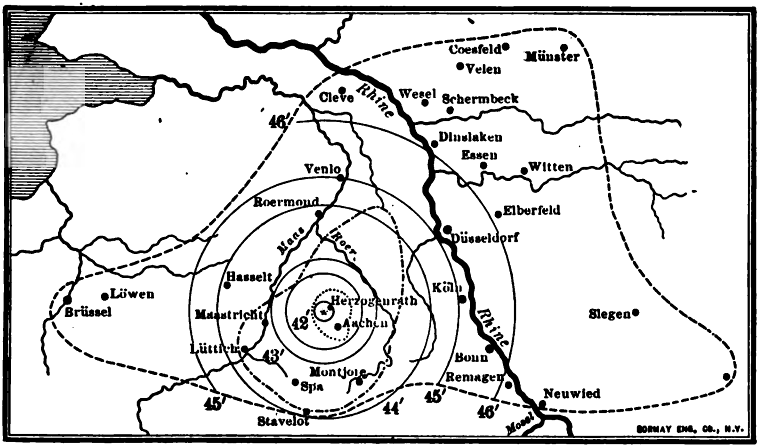



Fig. 211. Coseismal lines (lines connecting places feeling the shock at the same time) for each minute; Herzogenrath (Germany) earthquake of October 22, 1873. (Lasaulx.)

travel about 1.85 miles (3 km.) per second. Those which go through the earth travel more rapidly, at rates ranging from about 3.9 miles to about 5.7 miles per second.

**Distribution.** Over large parts of the globe, severe earthquakes are rare, but in certain regions they are, unfortunately, frequent. Earthquakes are likely to be rather frequent where geologic changes are in rapid progress, as along belts of young mountains where stresses are not yet adjusted, or at the mouths of great streams where deltas are accumulating, or about volcanoes where temperatures and strains are changing, or on the great slopes, particularly the submarine slopes, where adjustments to inequalities of stress are in progress. Not a few, however, occur where the special occasion is not obvious.

### *Geologic Effects of Earthquakes*

Geologically, earthquakes are of less importance than many gentler movements. Disastrous as they are to human affairs, they leave few distinct marks which are more than temporary.

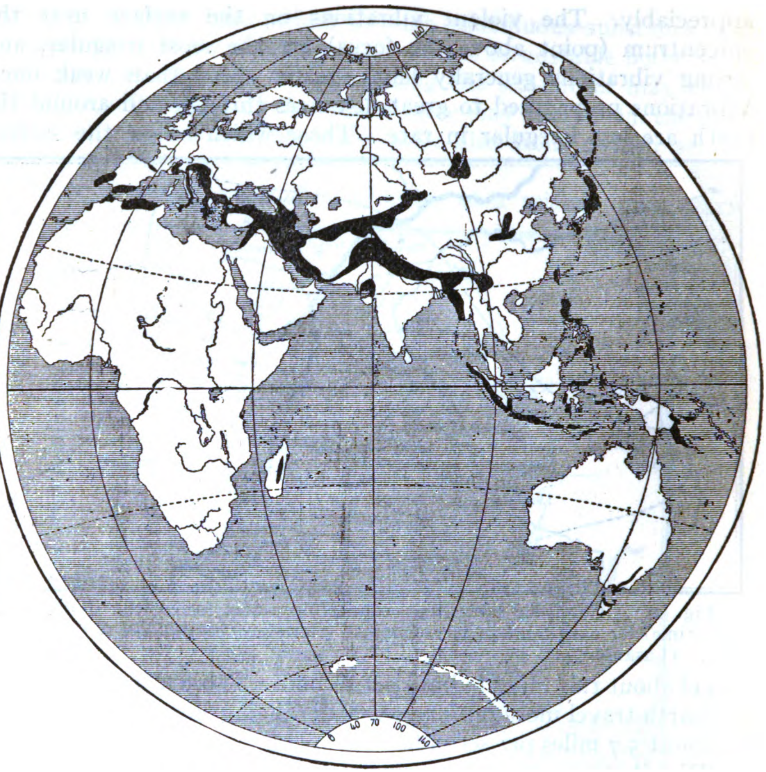



Fig. 212. Map showing in black the principal earthquake regions of the Old World. (Montessus de Ballore.)

**Surface changes.** During the passage of notable earthquake waves the solid rock may be fractured, though the fractures are rarely observable at the surface where the rock is covered by deep soil. In a few instances, surface-rock has been seen to be thoroughly shattered by the passage of an earthquake, as in the Concepcion earthquake of 1835. Joints which were closed before, may be opened during an earthquake. Thus in northern Arizona, not far from Canyon Diablo, there is a crevice traceable for a considerable distance which is said to have been opened during an earthquake (Fig. 214). Locally, it gapes several feet. During an earthquake which shook the South Island of New Zealand in 1848, "a fissure

Fig. 213. Map showing the principal earthquake regions of the New World. (Montessus de Ballore.)

was formed averaging 18 inches in width, and traceable for a distance of 60 miles, parallel to the axis of the adjacent mountain chain." [1] The development of fractures or the opening of joints is in some cases accompanied by faulting. This was the case in Japan during the earthquakes of October 28, 1891, when the surface on one side of a fissure, which could be traced for 40 miles, sank 2 to 20 feet (Fig. 215). There was also notable horizontal displacement, the east wall of the fissure being thrust locally as much as 13 feet to the north.

Circular surface openings or basins are developed in some cases

[1] Geikie, Textbook of Geology, 4th ed., p. 372.

during earthquakes, especially where the surface material is incoherent. This was the case during the Charleston earthquake of 1886,[1] and similar effects have been noted elsewhere. The basins are commonly supposed to be the result of the collapse of caverns, or other subterranean openings, the collapse causing the forcible ejection of water in some cases. Sand cones and craterlets are developed by some earthquakes (Fig. 216). During the California earthquake of 1906, the ground was much broken along the line of the fault which caused the shock (Fig. 217). Earthquakes may dislodge masses of rock in unstable positions, as on slopes or cliffs, causing slumps and landslides.

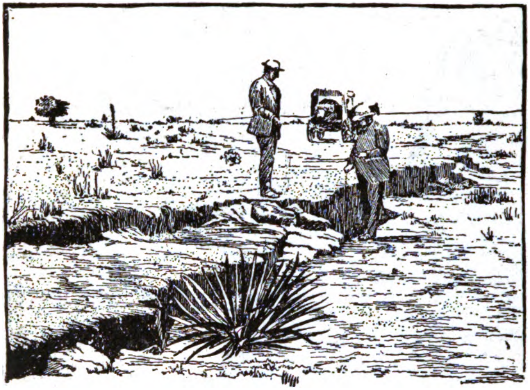


Fig. 214. Fissure produced by earthquake. Arizona.

Fig. 215. Fault in Japan, 1891. (Koto.)

[1] Dutton, Ninth Ann. Rept., U. S. Geol. Surv., pp. 209–528.

**Effects on drainage.** The fracturing of the rock may interfere with the movement of ground-water. After new cracks are developed or old ones opened or closed, the movement of ground-water adapts itself to the new conditions. It follows that a spring may cease to flow after an earthquake, while new ones break out where there had been none before. The character of the water of springs is in some cases changed, presumably because it comes from different sources after the earthquake. Joints may be so widened as to intercept rivulets. Where faults accompany earthquakes, they may occasion ponds or falls where they cross streams.

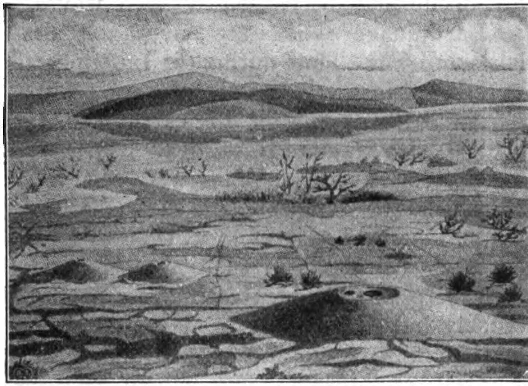


Fig. 216. Sand cones and craterlets observed after an earthquake in Greece, in 1861. (Schmidt.)

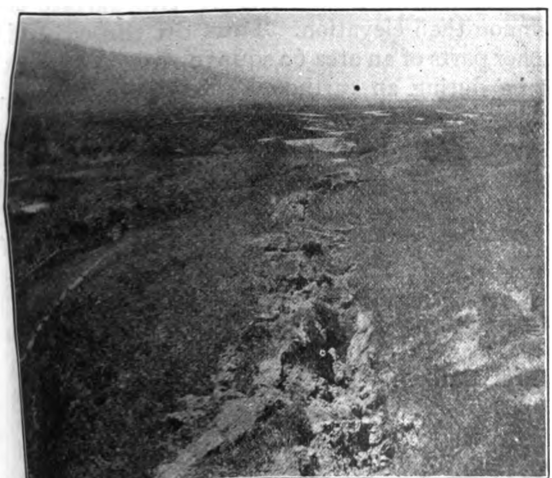


Fig. 217. Characteristic surface appearance of the California fault line, south end of Tomales Bay. (Photo. by Newsom.)

**Effects on standing water.** Some of the most destructive effects of earthquakes are felt along shores. The great sea-waves of the Lisbon earthquake (1775) and of the earthquake on the coast of Ecuador and Peru in 1868, were very

destructive. Such waves have been known to advance on the land as walls of water 60 feet high. They are most destructive on low coasts where the water sweeps over great areas of land. Great loss of life may be caused by such waves.

Earthquake shocks are remarkably destructive to the life of lakes and seas. Thus during the Indian earthquake of 1897, "fishes were killed in myriads as by the explosion of a dynamite cartridge. . . . and for days after the earthquake the river (Sumesari) was choked with thousands of dead fish. . . . and two floating carcasses of Gangetic dolphins were seen which had been killed by the shock."[1] This wholesale destruction of life is of interest since the surfaces of layers of rock, even of great age, are in some cases covered with fossils in such numbers as to indicate that the animals were killed suddenly and in great numbers, and their bodies quickly buried. It has been suggested that such rock surfaces may perhaps record ancient earthquake shocks.

**Changes of level.** Permanent changes of level accompany some earthquakes. Thus after the earthquake of 1822 "the coast of Chili for a long distance was said to have risen 3 or 4 feet." Similar results have occurred on the same coast at other times, and on other coasts at various times. Depression of the surface is perhaps even more common than elevation. Thus on the coast of India, all except the higher parts of an area 60 square miles in extent were sunk below the sea during an earthquake in 1762. Widespread depression in the vicinity of the Mississippi in Missouri, Arkansas, Kentucky, and Tennessee accompanied the earthquakes of 1811 and 1812. Some of the depressed areas were converted into marshes, while others became the sites of permanent lakes. Reelfoot Lake, mainly in Tennessee, is an example. Change of level is involved in much of the faulting which goes with earthquakes.

Changes of level are not confined to the land. Where earthquake disturbances affect the sea-bottom in regions of telegraph cables, the cables may be broken. In some such cases notable changes have been discovered when the cables were repaired. In one instance (1873) the repairing vessel off the coast of Greece[2] found about 2,000 feet of water where about 1,400 feet existed when the cable was laid. In another instance (1878) the bottom was so

[1] Oldham, loc. cit., p. 80.

[2] Forster, Seismology. Summarized in Am. Geol., Vol. III, 1889, p. 182.

"irregular and uneven for a distance of about two miles, that a detour was made and the cable lengthened by five or six miles." In still another case (1885) the repairing vessel found a "difference

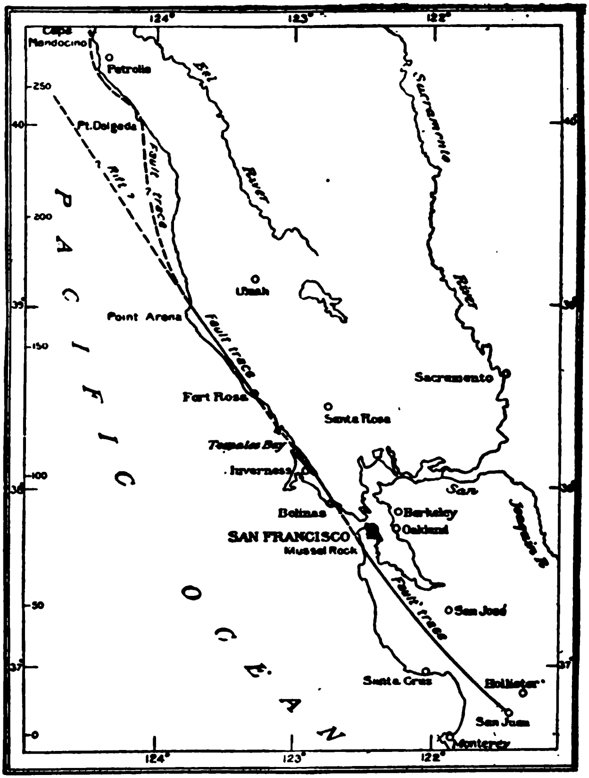


Fig. 218. Line of the fault where movement took place during the California earthquake of 1906. (U. S. Geol. Surv.)

of 1,500 feet between the bow and stern soundings." These records, if correct, point to sea-bottom faulting on a large scale.

### SECULAR MOVEMENTS

The minute and momentary oscillations of earthquakes are very unlike the slow movements of continents or ocean basins, or even the slow wrinkling of mountain folds. Rivers may wear down their channels across a mountain range as fast as it rises across

their courses, and the movements of continents are yet slower; but far apart as these contrasted movements are, they are doubtless associated in cause. Many earthquake shocks are but incidents in the formation of mountains or in the movements of continents.

Great movements may be classified variously, as (1) continent-making, (2) plateau-forming and (3) mountain-folding; as (1) general (*epeirogenic*) and (2) concentrated (*orogenic*); as (1) vertical and (2) horizontal; and dynamically, as (1) thrust and (2) stretching movements. These distinctions are analytical conveniences, but the various types of movement are not exclusive of one another, for continental movements may involve mountain-making, vertical movements involve horizontal movements in most cases, and stretching usually attends the outward bends of thrust folds.

**Present movements.** Observations on seacoasts show that some shores are rising slowly and some sinking slowly, *relative to sea level.* It is not certain what these movements are, *relative to the center of the earth.* Theoretically all parts of the coast may be sinking, some faster than others, while the ocean-surface goes down at an intermediate rate; or all parts may be rising, but at different rates; or again some lands may be actually rising relative to the center of the earth, and others sinking, while the ocean-level has an intermediate movement or none at all. We are accustomed to take the sea-level as a standard, as though it were stationary, which is probably not the fact. A general shrinkage of the earth is probably going on, carrying down the surface of both land and sea. It is possible that the shrinkage is so great that many of the upward warpings and foldings do not equal it. If this is true, most movements are really toward the earth's center. There is a popular predilection for regarding earth movements generally as "upheavals," and for regarding the rigid land as moving and the mobile sea-level as fixed. In reality, the sea is an extremely adaptive body which settles freely into the depressions of the lithosphere, and is shifted with every warping of the latter. Whatever change affects the capacity of the sea basins affects the sea-level. If the basins are increased, the sea settles deeper into them; if they are decreased, the sea spreads out more widely over their borders. The one thing that gives a measure of stability to the sea-level is the fact that all the great basins are connected, and so an *average* is maintained. For this reason the sea-level is the most convenient basis of reference, and has become the accepted datum-plane, not-

withstanding its instability and its complete subordination to the lithosphere. If there were some available mode of measuring the distance of surface points from the center of the earth, it would reveal much that is now uncertain respecting the real movements of the surface.

**Periodic and aperiodic movements.** The existence of land depends on protuberances of the surface of the lithosphere. If the lithosphere were perfectly spheroidal, water would cover it everywhere to a depth of nearly two miles. *To maintain the existence of land the protuberances must be renewed from time to time;* otherwise the land would in time be degraded to the lowest depths of wave action. Such renewal has been brought about again and again in geologic history. With every movement which restored the protuberances, the oceans seem to have withdrawn more completely within the basins, while the continents have stood forth more prominently until worn down again. This renewal of protuberances appears to have been *periodic in its great features*, with long intervals between. In these intervals, the land was worn down by rivers, waves, etc., and the sea encroached upon the lower parts of the continents,— the continental shelves. Before complete submergence was effected, renewed deformations checked the progress of submergence and rejuvenated the continents.

Beside the great periodic movements, minor warpings or oscillations of the surface have been in almost constant progress. Some of these are probably incidental to the larger movements, but others probably are due to local causes.

### *Minor Movements*

Gentle movements seem to have affected nearly every portion of the surface of the lithosphere at nearly all stages of its history. They have had much to do with the particular places and forms of deposits. Slow sinkings of sea-borders have permitted deposition to go on in shallow water for long periods without building the bottom up into land, and slow relative swellings of land tracts have renewed the sources of sediments for such deposits. Such movements shift shore lines, and with them the areas of erosion and deposition. These movements may have amounted to a few inches, or a few feet per century. In some cases they appear to have been reciprocal, one area being bowed up while another near by is bowed down. How far these are merely local or regional, due to loading,

unloading, changes of temperature, or other local causes, and how far they are the milder phases of great movements or incidental to them, it is difficult to decide.

### *The Great Periodic Movements*

1. **Mountain-folding.** Along certain tracts, the shell of the earth has wrinkled, forming folded mountains. The shell so folded, judged from the nature of the folds, seems to be no more than a few miles thick. The forces that caused the folding took the form of lateral thrusts. The folds themselves were usually lifted, showing that there was an upward component to the horizontal thrust, but the horizontal component was the dominant one. Some folds are nearly upright and symmetrical, and some inclined and asymmetrical, as illustrated in Chapter X. Where the folds lean, it is commonly inferred that the active thrust was from the side of the gentler slope, pushing the fold over toward the resisting side; but this is not a safe inference in all cases, for the original attitude of the beds has much to do with the way they yeild. Most systems of folded mountains embrace a series of roughly parallel folds, the whole forming an anticlinorium (Fig. 219).

**Distribution of folded mountains.** The location of folded mountains is near the borders of continents in so many cases that the relation is probably significant, but there are folded mountains far from coasts, as the Urals, the mountains of Central Europe and of Central Asia.

Fig. 219. Anticlinorium: diagrammatic. (Van Hise, U. S. Geol. Surv.)

Folding movements seem to have been very common in the early ages. The Archean rocks (Chapter XIII) are almost universally crumpled, and in many places in the most intricate fashion, and the Proterozoic formations are much folded. After the inauguration of the Paleozoic era, folding appears to have taken place chiefly at long intervals, and for any given period to have been concentrated along certain tracts. The Appalachian system is an example.

2. **Plateau-forming movements.** An important phase of massive movement was the relative settling or raising of great blocks or

segments of the earth, as though by vertical, rather than horizontal forces. The great plateaus are examples of one phase of this action, and perhaps the great "deeps" of the ocean bottom, and some of the basins or troughs (*Graben*) of the continents, are examples of the other. Most plateaus are made up of numerous blocks which have been moved by different amounts. At the surface, these blocks are separated by fault-planes, but below, some of the faults pass into flexures. Plateau-forming movements are to be compared

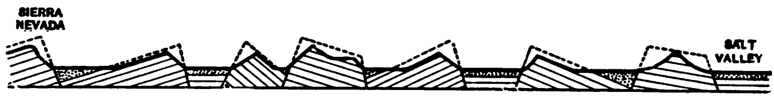



Fig. 220. Ranges of the Great Basin. Length of section, 120 miles. (Gilbert.)

with continent-forming movements rather than with mountain-foldings, differing from the former chiefly in magnitude. Plateaus may be regarded as parts of a continental mass that have suffered additional movement. Plateaus stand in some such relation to continents as one fault block of a plateau does to the whole plateau.

3. **Continent-forming movements.** These are widespread movements affecting large masses of the body of the earth, if not its whole outer portion. Two or more continents may be affected by similar movements at the same time, and it is the view of many geologists that all continents are affected simultaneously by movements of a like kind, resulting in emergence or submergence, while the ocean basins are affected by movements of the opposite phase. These movements are regarded as reciprocal, and parts of a world-wide adjustment. While well supported both by observation and theory, this view is not universally accepted. Movements of this class seem to have started early in the history of the earth, and to have been renewed from time to time, rejuvenating the continents and deepening the ocean basins. Under the view that the earth is essentially solid throughout, these movements are regarded as extending down to great depths, while mountain folding is regarded as but the wrinkling of the earth's skin to fit its changed body.

Downward movements are regarded as the primary ones, and horizontal movements as a necessary result of them. The underlying cause of movement is believed to be shrinkage due to an increase in the density of the earth, caused by gravity and by molecular and sub-molecular attractions. Cooling is probably a lesser cause of shrinkage. The master movement is thought to be the

sinking of the ocean basins, whose specific gravity is greater than that of the continents. If the ocean basins and the continents, respectively, be regarded as the surfaces of great segments of the earth all of which are crowding toward the center, the stronger and heavier segments may be conceived to take precedence, squeezing the weaker and lighter ones between them. The consequent swelling up of the lighter segments accounts for the relative protrusion of the continents.

The area of the depressed segments is almost exactly twice that of the protruding ones, if we count the 10,000,000 square miles of the continental shelves as parts of the latter. In millions of square miles, the depressed segments are approximately as follows: the Pacific 60, the Indian 27, the South Atlantic 24, the North Atlantic 14, leaving 8 for minor depressions. The elevated segments are the Eurasian 24, the African 12, the North American 10, and the South American 9, leaving 10 for the minor blocks.

The downward movement of the larger segments and the crowding of the smaller and lighter segments between them involves deformation of the latter. The movements that spring from the deeper crowding affect the continental protuberances generally, or at least broadly, while the crowding of the more superficial parts affects the lands more locally. According to this view, it is obvious there should be special bowings on the borders of the continental segments, and this tallies with the archings common on borders of the continents, even where there is no folding. The shell of the earth is free at the surface, and as a result, folding and faulting are the modes of easiest accommodation there, while the deeper parts, under great pressure, must be deformed throughout.

The periodicity of the movements is assigned to the rigidity of the thick, massive segments which must be deformed to effect readjustment after shrinkage. Because of this rigidity, stresses accumulate for a time until they are equal to the resistance opposing them. A further increase of the stresses then causes yielding and readjustment. When masses under stress once begin to yield in the direction of their free surfaces, their attitudes for resistance become less favorable, and hence the yielding continues until the stress is eased. After this another period is required for stresses to accumulate sufficient to produce another general deformation. Meantime the minor stresses that may remain, or may be produced by the great deformations, tend to ease themselves and thus give rise

to minor movements (p. 219). Other minor movements are doubtless due to local causes.

**Extent of the movements.** Between the highest elevation of the land and the lowest depth of ocean, there is a vertical range of nearly twelve miles. From the Tibetan plateau, where a considerable area exceeds three miles in height, to the Tuscarora deep, where a large tract exceeds five miles in depth, the range is eight miles. This represents fairly the vertical range of differential movement of large areas, though not areas of continental size. The average height of the continents is about three miles above the average bottom of the oceans, and this may be taken roughly as the differential vertical movement of the segments of continental dimensions.

If the protruding portions of the lithosphere were graded down and the basins graded up to a common level, this level would lie about 9,000 feet below the surface of the sea. Referred to this datum plane, the continents have been squeezed up *relatively* about two miles, and the basins have sunk about one mile. The *total downward movement*, representing the total shrinkage due to increase of density, is quite unknown, but from theoretical considerations, it would appear to be far greater than the differential movement. This would mean that all segments have probably moved toward the center, the basin segments about three miles more than the continental.

The extent of the *lateral movements* of the shell has a peculiar interest, for it has a theoretical bearing on the extent of the downward movements. Every mile of descent of the crust represents more than 6 miles ($6.28 = 2\pi$) shortening of the circumference. If the vertical movements were limited to the *relative* ones just named, the mile of descent of the ocean basins would give but little more than 6 miles excess of circumference for lateral thrust and the crumpling of the shell. How far does this go in explaining mountain folds? The shortening represented by the folds of the Alps has been estimated at 74 miles;[1] the shortening for the Appalachians in Pennsylvania, not including the crystalline belt on the east, at 16 miles;[2] that of the Laramide Range in British America at 25 miles.[3]

[1] Heim, Mechanismus der Gebirgsbildung, p. 213.
[2] Chamberlin, R. T., Jour. Geol., vol. 18, p. 255, 1910.
[3] McConnel, Geol. Surv. of Canada, p. 33 D, 1886.

These estimates cannot be taken as measurements, but they are sufficiently close approximations to make it clear that the shortening of the shell involved in mountain folding is large. These estimates represent only that shortening of the circumference effected at certain times and places; the whole shortening of a circumference involves the shortening implied by all the transverse folds on a given great circle. Usually a great circle does not cross more than one or two strongly folded tracts of the same age, from which it is inferred that the shortening on each great circle at any one time was concentrated largely in a few tracts running at large angles to each other. If the folding of one of the main mountain ranges be doubled, it may perhaps represent roughly the shortening for the circle at right angles to it, *for its own period of folding.* If one is disposed to minimize the amount of folding, the estimate of the shortening may perhaps be put at 50 miles on a circumference, for each of the great mountain-making periods; or, if disposed to make the estimate large, the shortening may be put at 100 miles. For the whole shortening since the beginning of the Paleozoic era, perhaps twice these amounts might suffice. Assuming the circumferential shortening to have been 50 miles during a given great mountain-folding period, the appropriate radial shortening is 8 miles. For the more generous estimate of 100 miles, it is 16 miles. If these estimates are doubled for the whole of the Paleozoic and later eras, the radial shortenings are 16 and 32 miles, respectively. If these or similar figures are correct, it is clear that the surface of the earth has sunk toward the center by an average amount greater than that of the highest mountains above mean sphere level, since the beginning of the Paleozoic era. The shortening for earlier eras can hardly be estimated from present data.

### *Causes of Secular Movements*

The volume of the earth is affected by two sets of forces, acting in opposition to one another, (1) *the concentrating forces*, consisting of (a) gravity and (b) molecular and sub-molecular attractions, and (2) *the forces which resist concentration* consisting of (a) heat and (b) molecular and sub-molecular resistances.

1. **The centripetal forces.** The best known of the concentrating forces is gravity, which tends to bring all parts of the earth as near the center as possible, the heavier beneath the lighter. The gravitative force of the earth causes a pressure of about 3,000,000 atmospheres at its center, and lesser pressures at lesser depths. Gravity acts all the time, and tends to bring about greater density wherever molecular movement permits.

In addition to gravity, there are attractive forces between molecules, atoms,

ions, and electrons, which co-operate with gravity in accordance with laws of their own. Their general effect is to make matter denser. The extent of their operation is undetermined, but there is ground for thinking that the density of the interior still may be increasing by their action. It is known that substances which crystallize in a given way under surface pressures may be changed into denser forms under higher pressures. Re-aggregation in the interior thus probably means increased density, and it may be going on constantly. While knowledge on this point is inconclusive, it is permissible to entertain the view that gravitational, molecular, atomic, and sub-atomic forces have been and are still at work tending to increase internal density. It is even conceived that this may be a chief (if not *the* chief) cause of earth-shrinkage.

2. **The resisting agencies.** The condensing agencies are more or less held in check by resisting agencies. Of these heat is the most familiar. It is abetted by the molecular and atomic arrangements which exist at any given time, and which resist change, and by factors in the ultimate structure of matter, not well understood. It has been usual to regard the primitive state of the earth as one of intense heat, and to assign its subsequent reduction of volume almost solely to loss of heat; but this is not the view here favored. On the contrary, the heat of the earth is supposed to have been developed chiefly by reduction of volume and by radio-activity, and the heat thus developed is one of the forces which check further decrease of volume. Loss of heat is, of course, a cause of shrinkage, but its effect is thought to be less than that of molecular and sub-molecular rearrangements of the material of the earth, resulting in greater density. The loss indeed may not be greater than the new heat generated in the shrinkage.

*Observed temperatures in deep excavations.* As the earth is penetrated below the zone of seasonal changes, by wells, mines, tunnels, and other excavations, the temperature is almost invariably found to rise, but the rate of rise is far from uniform. If we set aside as exceptional the unusually rapid rise near volcanoes and in other localities of obvious igneous influence, the highest rates are more than six times the lowest, the range being from 1° F. in 20 feet, to 1° in 135 feet,[1] with an average of 1° in 50 to 60 feet. The recent deep borings in which temperatures have been carefully recorded, indicate a slower rate of rise, say 1° for 80 feet. It is not probable that the observed rates of increase continue to the center. One degree in 60 feet, continued to the earth's center would give a temperature of 348,000° Fahr., and 1° Fahr. in 100 feet would give 209,000° Fahr. It is probable that the rate of increase diminishes with depth, and that the temperatures cited above are far in excess of those actually existing at the center.

*Amount of loss of heat and shrinkage.* The amount of loss of interior heat may be estimated from that which is observed to be passing outward through the rocks, or by computations based on the estimated temperature gradients and with the known conductivity of rock. Estimates of the loss of heat in 100,000,000 years range from 10° C. (18° Fahr.) (Tait) to 45° C. (81° Fahr.), for the whole earth. This is an exceedingly small result, and emphasizes the low conductivity of rock. With this amount of cooling, the shrinkage resulting has been calculated. For a loss of 10° C., the circumferential contraction is calculated to be 1.6 to 2.35 miles; for a loss of 45° C., 7.27 to 10.5 miles. These results are so small (cf.p. 223)

[1] 1° F. for 250′ down to 8,000 feet, is reported from the Rand., S. Af. Mining World, Jan. 7, 1911, p. 2.

that unless there is serious error in the estimates, cooling would seem to be *a very inadequate cause for the shrinkage implied by mountain folds, overthrust faults, and other crustal deformations.* This inadequacy has been urged strongly by various students of the problem.[1] In view of the apparent incompetency of external loss of heat, the possibilities of distortion from other causes deserve consideration.

Shrinkage from denser rearrangement of material already has been referred to (p. 225), and the transfer of heat from deeper to more superficial parts will be discussed in Chapter X. A lowering of the average temperature of the inner half of the earth 500° C., and a raising of the temperature of the outer half an equal amount, would cause a lateral thrust of about 83 miles. Some transfer of this kind is among the theoretical possibilities under the planetesimal hypothesis. The process could not continue indefinitely; but computations imply that it still may be in progress.

*The rise of lavas.* If lavas are forced out from beneath the surface, a compensatory sinking of the outer shell will follow. The great lava-flow of the Deccan is credited with an area of 200,000 square miles, and a thickness of 4,000 to 6,000 feet. This would form a layer about 5 feet thick if spread over the whole surface of the globe. The compensatory sinking would cause a lateral thrust, on any great circle, of about 31 feet only. It requires a very generous estimate of the lavas poured out since the beginning of well-known geological history to cause a horizontal thrust amounting to any appreciable part of that involved in the folding of a typical mountain system. The case is different, however, if we go back to Archean times when the amount of extrusion was very large. Notable distortion may have arisen from the extravasation of the lavas of that era.

Intrusions of lava rising from lower to higher levels in the earth would have a dynamic effect similar to that of extrusions, so far as the outer part of the earth is concerned, and the amount of intrusive rock is probably far greater than that of extrusive.

There are other possible factors in deformation which will not be discussed here.

*References on crustal movements.*

Dana, Manual of Geol., 4th ed., p. 345 et seq.; Willis, The Mechanics of the Appalachian Structures, 13th Ann. Report, U. S. Geol. Surv., Pt. II (1893), pp. 211–282; LeConte, Theories of Mountain Origin, Jour. Geol., Vol. I (1893), p. 542; Gilbert, Jour. Geol., Vol. III (1895), p. 333, and Bull. Phil. Soc. of Washington, Vol. XIII (1895), p. 31; Van Hise; Estimates and Causes of Crustal Shortening Jour Geol., Vol. VI (1898), U. S. Geol. Surv. (1904), pp. 924–931; A. Geikie, Text-book of Geology, 4th ed., pp. 672–702; Chamberlin and Salisbury, Geologic Processes and their results, Chapter IX; R. T. Chamberlin; The Appalachian folds of Central Pennsylvania, Jour. Geol. Vol. XVIII (1910) pp. 228–251.

*Map work.* See Plates CLXV to CLXVII of Professional Paper 60, U. S. Geol. Surv., and Exercise XVII, Interpretation of Topographic Maps.

[1] Fisher, Physics of the Earth's Crust, Chap. VIII; and Dutton, Penn. Monthly, Philadelphia, May, 1876.

# CHAPTER IX

## VULCANISM

*Vulcanism* is the term applied to all movements of lava toward the surface of the earth, and is made to include certain other phenomena closely connected with these movements. In its rise, some lava reaches the surface, giving rise to eruptive or volcanic phenom-

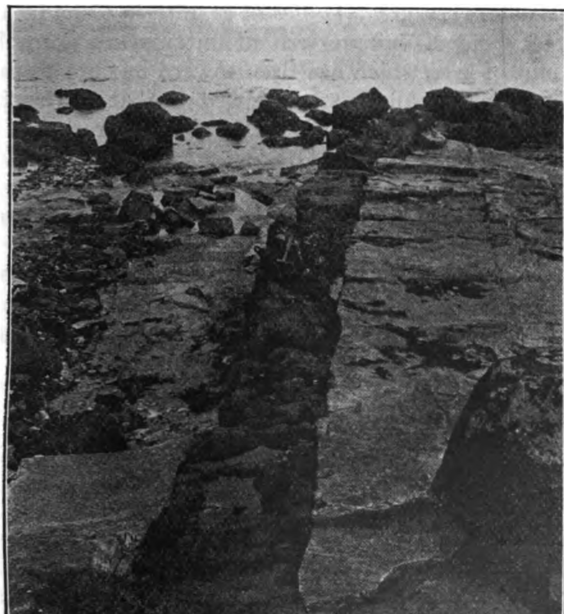


Fig. 221. A dike two feet wide, cutting through sandstone. Arran, coast of Scotland. (H. M. Geol. Surv.)

ena; and some intrudes itself into the outer formations of the earth and congeals there. The first gives rise to *volcanic* rocks, and the second to *plutonic*. The first are *extrusive;* the second, *intrusive;* the first constitute *eruptions;* the second, *irruptions*. The fundamental nature of the two phases of vulcanism is the same.

## 1. INTRUSIONS

Fluid rock forced into fissures and solidified there forms *dikes* (Fig. 221); forced into chimney-like passages it forms *pipes* or *plugs;* insinuated between beds of other sorts of rock, it forms *sills;* and accumulated in considerable bodies which arch the strata up over them, it forms *laccoliths* (Fig. 222). If it breaks and lifts its cover, instead of arching it up, it is a *bysmalith.* Some laccoliths and bysmaliths are large enough to make good-sized mountains, of mound-like form. The Henry Mountains of Utah are laccoliths. Still more massive intrusions of igneous rock are sometimes called *batholiths.* The very great bodies of granite in Canada and along the axes of some of our western mountains are examples. The total amount of lava which has risen toward but not to the surface probably far exceeds all that has flowed out at the surface. Intrusions are usually seen only after erosion has removed the rocks which overlay them.

There appear to be cases where intrusions come so near the surface as to develop explosive phenomena at the surface. At any rate, it is certain that occasional violent explosions take place where no lava comes to the surface. The explosion may be due to an intrusion of lava, or it may be due to the penetration of surface-waters to hot rocks that have remained uncooled from previous volcanic action. A case of this kind occurred in Japan in 1888, where there was a sudden and violent explosion which blew away a considerable part of the side of a volcanic mountain which had not been in eruption for at least a thousand years. The explosion filled the air with ashes and debris like a violent volcanic eruption. There was but one eruption, and within a few hours the cloud of dust had disappeared and the phenomenon was ended. No lava was extruded.

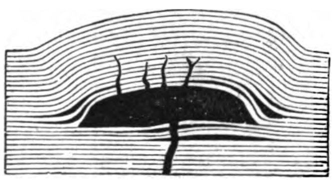


Fig. 222. Ideal cross-section of a laccolith with accompanying sheet and dikes. (Gilbert, U. S. Geol. Surv.)

Intruded igneous rock changes the rock into which it is forced. Thin dikes and sills produce little effect, but greater masses alter the adjacent rock notably. The metamorphism is effected by (1) the heat, (2) the pressure incident to the intrusion, and (3) the chemical changes stimulated by the heat, water, and gases issuing from the lava, and by pressure in the presence of ground-water.

## 2. EXTRUSIONS

When molten rock is forced to the surface it gives rise to the most impressive of all geological phenomena. The energies acquired in the interior under great compression here find sudden relief. Enclosed gases may expand with extreme violence, hurling portions of lava to great heights and shattering them into fragments, special forms of which are called bombs, cinders, ash, etc., all of which constitute *pyroclastic* material. Much of the explosive violence of volcanoes has been attributed to the contact of the hot rising lava with ground-water.

There are two phases of extrusion, and at their extremes they are contrasted strongly. The one is explosive ejection, attended in some cases with great violence; the other a quiet out-welling of the lava. More or less closely related to these two phases of extrusion are two classes of conduits, the one, *restricted openings*, such as pipes, ducts, or limited fissures, from which the amount of lava extruded is relatively small and forms cones; the other, *great fissures* out of which the lava pours in great volume and from which it spreads widely. The extent of the spreading of lava into thin sheets is due more to the mass and fluidity of the lava than to the form of the outlet. The stupendous outflows of certain geologic periods appear to have issued mainly from extended fissures.

### *Fissure Eruptions*

The chief known fissure eruptions of recent times are the vast basaltic floods of Iceland; but at certain times in the past there have been prodigious outpourings of lava, flow following flow, making formations thousands of feet thick and covering thousands of square miles. One of these occurred in Tertiary times in Idaho, Oregon, and Washington (Fig. 223), where about 200,000 square miles were covered with lava, aggregating in places some 2,000 feet in thickness. Still earlier, in the Cretaceous period, there were enormous flows on the Deccan, covering a like area to the depth of 4,000 to 6,000 feet. Still earlier, in the Keweenawan period, an even more remarkable succession of lava-flows in the Lake Superior region developed a series of igneous rocks of almost incredible thickness. In these cases there is little evidence of explosive or other violent action, and little pyroclastic material. For the most part these wide-spreading flows are composed of basic material. Massive outflows of this class are the greatest examples of extrusions,

though not now the dominant type. It has been thought that the volcanic type of extrusion followed fissure eruptions as a phase of decline; but this view has not been substantiated.

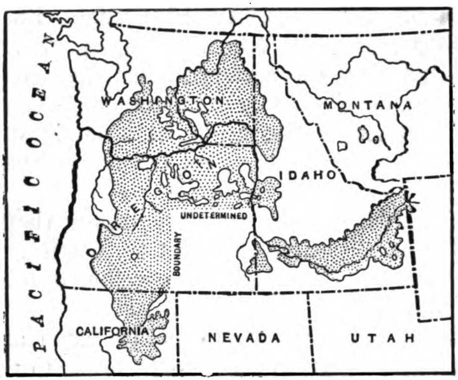



Fig. 223. Lava-flows of the northwestern part of the United States.

*Volcanoes*

A volcano is a circumscribed vent in the earth's crust, out of which hot rock, gases, and vapors issue. The ejected material is generally built up into mounds or cones (Figs. 224–225), which are often called v o l c a n o e s, though they are really the products of volcanoes. So long as a volcano is active there is likely to be a depression, or *crater* (Fig. 226), in the top of its cone. The crater connects downward with the source of lava at unknown

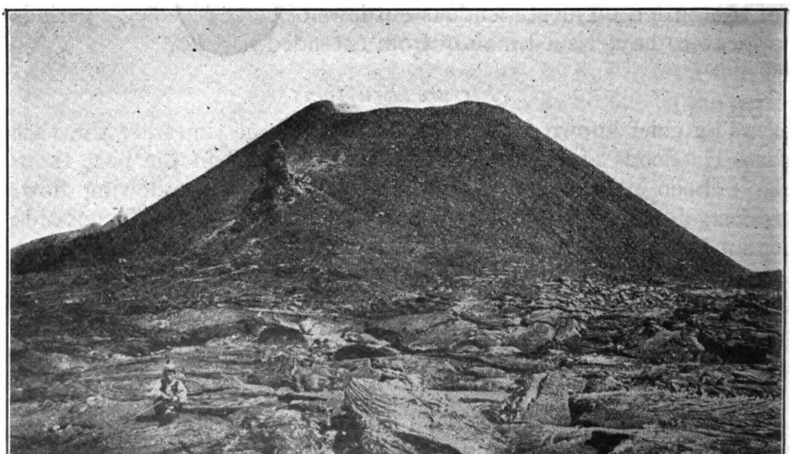


Fig. 224. Cinder cone forming the summit of Mt. Vesuvius.

depths. Craters may be a mile or more across, but most of them are smaller, some much smaller. After sufficient erosion, extinct vol-

canoes show that the former passageways leading down toward the sources of lava vary much in size and shape.

The exact number of volcanoes now active is not known, because most volcanoes are active periodically only, and it is impossible to say whether a volcano which is now quiescent is extinct or only resting. It is safe to include 300 in the active list, and the number may reach 350 or more. The number that have been active so recently that their cones remain distinct is several times as great.

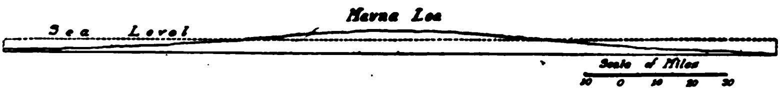



Fig. 225. Profile of the cone of Mauna Loa. Vertical scale same as horizontal. (U. S. Geol. Surv.)

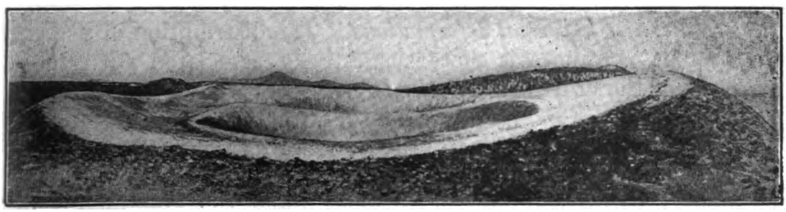


Fig. 226. Sketch of the crater of cinder cone near Lassen Peak, Cal., showing the peculiar feature of two rings. The funnel is 240 feet deep. (U. S. Geol. Surv.)

**Distribution.** 1. *In time.* In the earliest known ages, igneous action appears to have been very widespread. No great area of the oldest (Archean) rocks is known where the formations are not largely igneous. From the Paleozoic to the present, the distribution of volcanic action over the surface seems to have been, in a general way, much what it is to-day; that is, certain areas were affected at times by volcanoes, while other and larger areas had few or none. This is not equally true of all periods, as will be seen in the historical studies that follow. There were periods when volcanic activity was widespread and energetic, and others when it was limited. The known facts do not indicate a steady decline, but rather a periodicity; at least this is so for the portion of the globe that is now known well enough to warrant conclusions.

2. *Relative to land and sea.* Active volcanoes are located chiefly along the borders of continents, and within great oceanic basins (Fig. 227). On this account, the sea-water was formerly supposed to have some causal connection with their activity, and

the presence of chlorine in the volcanic gases has been urged in support of this view. Volcanoes, however, are not distributed so equably and exclusively about the several oceans as to give this conclusion force. Volcanoes are numerous within and around the Pacific, the greatest of the oceans, and in and around the Mediterranean, a much smaller body of water; but they are not especially abundant in or about the Atlantic. On the other hand, there are existing or very recent volcanoes in the interior of Asia, Africa, and America. If volcanoes were dependent upon proximity to the sea, they should have had close relations to it in the past, as much as now; but in recent periods there has been much volcanic activity in western America, far from the sea, and in the heart of Asia and Africa. In older periods, it is still less clear that there was any connection between volcanoes and oceans.

3. *Relative to crustal deformations.* The distribution of present and recent volcanoes is more suggestively associated with those portions of the crust *that have undergone movement in comparatively recent times, or are still moving.* The great mountain belt stretching from Cape Horn to Alaska and thence onwards along the east coast of Asia is dotted with active and recently extinct volcanoes. The tortuous zone of mountainous wrinkles about the Mediterranean, and thence eastward to the Polynesian Islands, is another notable volcanic tract. These two belts include the greater number of existing and recent volcanoes on the land.

4. *In latitude.* Volcanoes appear to have no specific relation to latitude. Mounts Erebus and Terror amid the ice-mantle of Antarctica, and Mount Hecla in Iceland, as well as the numerous volcanoes of the Aleutian chain, give no ground for supposing that volcanoes shun the frigid zones, while the numerous volcanoes of the equatorial zone imply that they do not avoid the torrid belt.

5. *In curved lines.* In the Aleutian and Kurile Islands, and elsewhere, there is a linear arrangement of volcanoes, with appreciable curvatures, the convexities of which are turned toward the adjacent ocean. In other cases there is a linear arrangement without appreciable curvature, as in the Hawaiian range. In some cases, volcanoes are bunched irregularly, as in some of the groups of volcanic islands of the Pacific (Fig. 227).

**The relations of volcanoes.** A significant feature in connection with volcanoes is the apparent sympathy between adjacent vents in some cases, and their entire independence in others. The recent

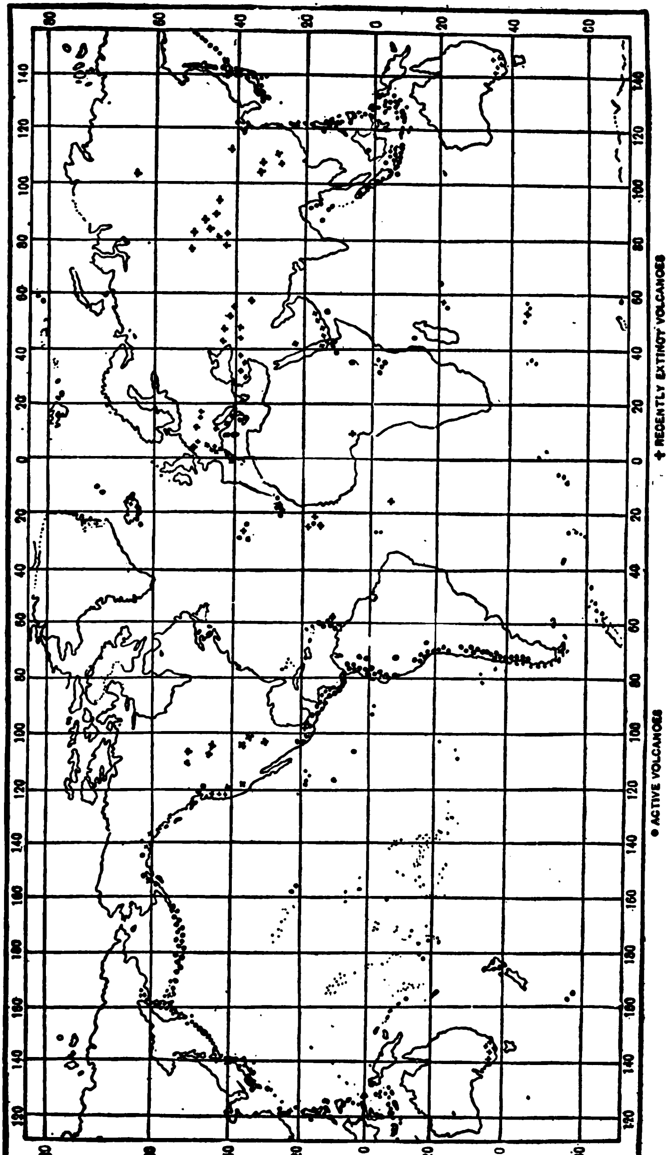



Fig. 227. Map showing distribution of volcanoes. (After Russell.)

(1902) outbursts in Martinique and St. Vincent, and the symptoms of activity at the same time in other places, seem to point clearly to sympathy. On the other hand, the independence of some neighboring vents, as those of Mauna Loa and Kilauea in Hawaii, is extraordinary. These two volcanoes are only about twenty miles apart, the one on the top and the other on the side of the same mountain mass. The crater of Loa is about 10,000 feet higher than that of Kilauea, and yet, while the latter has been in constant activity as far back as its history is known, the former is periodic. The case is the more remarkable because of the greatness of the ejections. The outflow of Mauna Loa in 1885 formed a stream 3 to 10 miles in width and 45 miles in length, with a probable average thickness of 100 feet, and some of its other outflows were nearly as massive. Besides this massiveness, there were extraordinary movements of the lava within the crater, if the testimony of witnesses may be trusted. But throughout these great movements in the higher crater, the lava-column of Kilauea, 10,000 feet lower, continued its quiet action without sensible relation to its boisterous neighbor. No difference in specific gravity that could account for a difference in height of 10,000 feet has been observed or can be presumed. It seems a necessary inference, therefore, that the lava-columns in the two volcanoes have no connection with each other, or with a common reservoir. The tops of some lava-columns stand about 20,000 feet above the sea, while others emerge on the sea-bottom far below sea-level. This range of elevation tells its own story as to the independence of vents.

Eruptions seem to be somewhat more common when atmospheric pressure is high than when low, doubtless because the increased atmospheric weight on a large area of the crust, aids in forcing out lava and volcanic gases. This can be effective only when other forces have almost accomplished the result. Eruptions seem also to be more common when tidal strains favor them, for like reasons. In the same class are probably to be put the effects of heavy rains. Such factors are regarded as mere incidents, of no moment as real causes of vulcanism, but of some value in determining the moment of eruption.

**Periodicity.** Most volcanoes are intermittent in their action, long periods of dormancy intervening between periods of activity. Some volcanoes supposed to be extinct have renewed their activity with terrific violence. Their periodicity awaits an explanation,

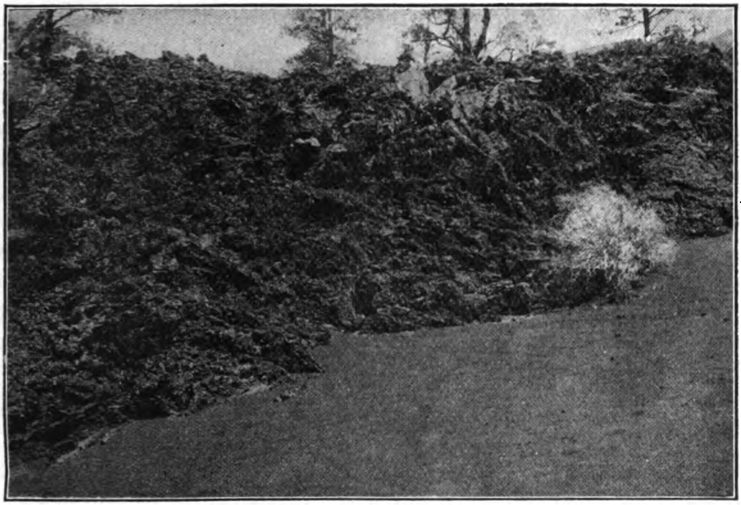


Fig. 228. The edge of an old stream of lava, showing (1) its broken character due to movement after the outside had hardened, and (2) the steep slope of the stream of stiffened lava. Near Flagstaff, Ariz. (Fairbanks.)

but the temporary quiet very likely means an exhaustion of the supply of gas or lava, or both.

**Products of volcanoes.** 1. *Pyroclastic material.* The fragmental materials which are blown out of a volcano are, as a rule, portions of lava which solidified before ejection, or during their flight in the air. From masses of rock tons in weight, the fragments grade down to particles of dust. The dust particles (often called *ash*) are thrown high into the air in some cases, and, caught by the winds, are shifted incredible distances (p. 13). In some cases, beds of volcanic ash many feet in thickness (as those of Nebraska) are found far from any known volcanic center. The extremely fine ash from the great explosion of Krakatoa floated several times around the earth in the equatorial belt, and spread northward into the temperate zones.

*Liquid rock, lava.* The term lava is applied to all kinds of liquid rock, and also to the solid rock formed when fluid rock congeals. The various phases assumed by lava, on solidification, have been noted in connection with igneous rocks. Lava never flows so freely as water, and is, in many cases, very stiff or viscous. The distance to which it flows depends on its liquidity, its amount, and the slope of the surface on which it is poured out.

As lava flows, its upper surface may cool so much as to become hard while the interior is still fluid. The fluid part may then break out at the side or end of the hardened shell and flow away, leaving a hollow crust of solidified lava. On further cooling, the shell contracts and cracks, and perhaps caves in. The hardened surface of a lava-flow may be broken by the movement of the fluid lava below, and the solid fragments be displaced and upturned so as to give the surface a jagged appearance.

3. *Gases and vapors.* The gases and vapors which issue from volcanoes are of many kinds. Among the commoner ones are those of water ($H_2O$), carbon dioxide ($CO_2$), carbon monoxide ($CO$), chlorine ($Cl$), hydrochloric acid ($HCl$), sulphur dioxide ($SO_2$), and hydrogen sulphide ($H_2S$); but with these more important ones there are many others. Oxygen and hydrogen are generally present, perhaps produced by the dissociation of the elements of water. Some of the gases are poisonous, and, as in the case of Pelée, their temperature is in some cases so high as to be destructive to life.

**Formation of lava cones.** Lava usually flows away from a vent in streams which solidify before running far. As the lava-streams flow in different directions at different times, the total effect is a low cone formed of radiating tongues of lava. The streams may congeal before they reach beyond the base of the cone, and not rarely while yet on its slope. The volcanic cones formed of lava have low slopes, since the fluidity of the lava prevents the development of high gradients. It is, however, the exception rather than the rule, that the cone is made up mainly of lava-streams, though the great Hawaiian volcanoes are of this class. The form of the cone, when composed chiefly of lava, is also affected by the mass of the outflow and by the fluidity of the lava. Other things being equal, the larger the outflow at a given time, the more widely it distributes itself, and the flatter the cone.

*Cinder-cones.* The larger portion of the lava blown into the air by expanding gas-bubbles falls back in the immediate vicinity of the vent and builds up cinder-cones. This fragmental matter may be disposed more or less symmetrically, making a cone with steep slopes (Fig. 224).

*Minor cones.* Small or temporary vents formed as offshoots from the main vents may give rise to secondary or "parasitic" cones. These may be numerous, as in the case of Etna, and so important that a volcanic mountain becomes a compound cone.

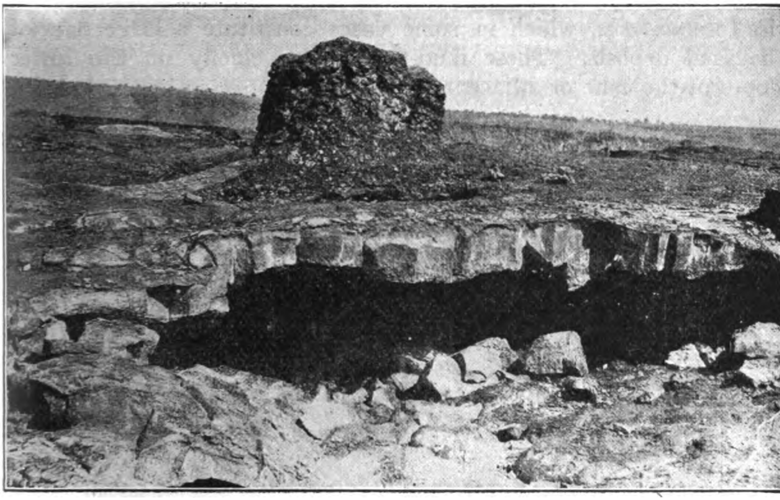


**Fig. 229.** Spatter-cone and cavern. Kilauea, Hawaii. (Photo. by Libbey.)

A still more subordinate type of cone is the "spatter-cone" formed about small vents that eject little dabs of lava which form chimneys, cones, domes, etc. Spatter-cones (Fig. 229) may arise from the surface of the lava-flows themselves.

From most existing volcanoes both lava-flows and fragmental ejecta are given forth, and the resulting cones are composite in material. Lava breaks through the side of a cone more frequently than it overflows its summit, and this gives rise to irregularities of form and structure. Cones also are subject to partial destruction both by outbursts of lava and by explosions. As a result, many volcanic regions show old, partially destroyed craters, as well as new and more perfect ones.

In violent eruptions, steam, accompanied with much ash, is shot up to great heights, rolling outwards in cumulus or cauliflower-like forms (Fig. 230). In the more violent explosions, these columns are projected several miles. In the phenomenal case of Krakatoa, the projection was estimated at seventeen miles. By reason of its great expansion as it rises, and by its contact with the colder air, steam is condensed quickly, and prodigious floods of rain accompany many an eruption. This rain, carrying down a portion of the ash and gathering up much that had previously fallen, gives

rise to *mud-flows*, which in some cases constitute a large part of the final deposit. These mud-flows lodge chiefly on the lower slopes of the cone or adjacent to its base.

The common view that lava is melted rock, is hardly the correct one. At any rate, it is at least equally correct to regard it as a solution of mineral matter in mineral matter. A familiar illustration will show what is meant. If ice and salt are mixed at a temperature of 30° F., the two form a liquid, though the temperature is too low to melt either. We say the salt is dissolved, but it would be

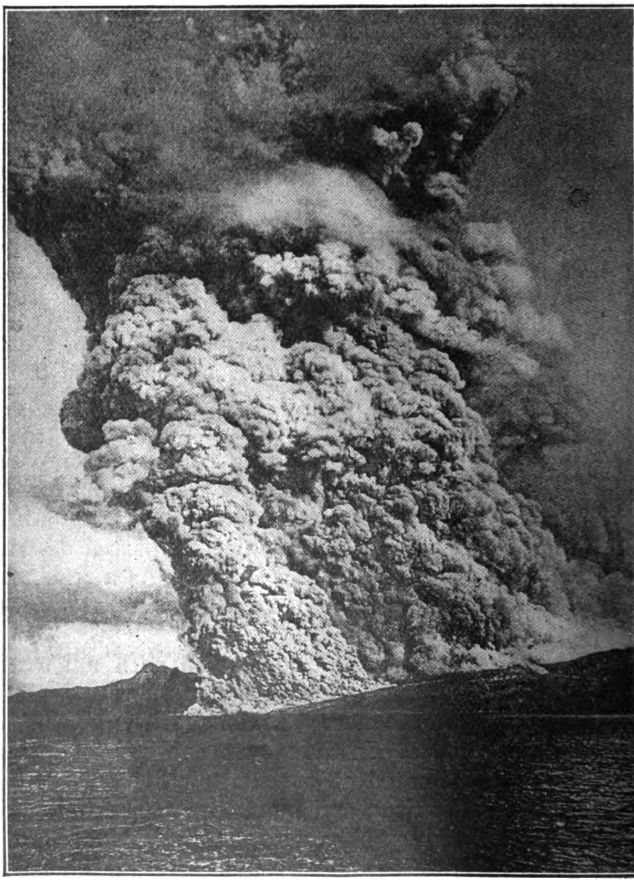


Fig. 230. The eruption cloud of Pelée, December 16, 1902. (Lacroix.)

just as correct to say that the ice is dissolved. The two minerals, ice and salt, are dissolved in each other, and the solution takes place at a temperature below

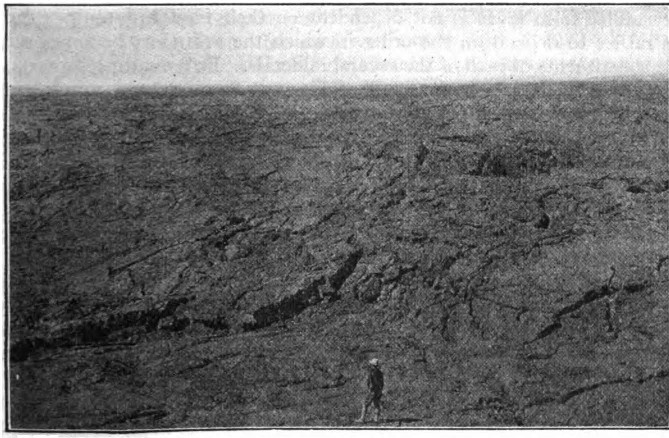


Fig. 231. Relatively smooth lava surface near the Jordan craters, Malheur Co., Ore. (U. S. Geol. Surv.)

Fig. 232. Ropy surface of lava, Mauna Loa, flow of 1881. (Calvin.)

the melting point of either. Something of the same sort appears to take place when rock becomes liquid. The distinction between such solutions and molten rock is not very sharp, but it is essential to know that the order in which the minerals crystallize from lavas is not dependent on their melting temperatures. It appears rather to depend on the order in which the solution becomes saturated with the constituents of each of the several minerals. For example, quartz, which has a very high melting-point, may crystallize out from a lava much later than minerals which have lower melting temperatures. The solutions are exceedingly complex, and include a wide range of chemical substances. Chief among them are silicates of aluminum, potassium, sodium, calcium, magnesium, and iron (Chapter X), with minor ingredients of nearly all known substances. Gases as well as rock materials enter into the composition of the igneous rock. When lava is cooled suddenly, the result is glass, every part of which has essentially the same composition that the liquid had, but even in this case some of the gases of the lava escape. If the cooling is slower, the various substances in the mixture crystallize out into minerals in the order in which they severally reach saturation. This involves the principle that solubility is dependent on temperature, and that as the temperature sinks the degree of solubility declines, and the saturation-point for some constituents of the solution is reached earlier than that for others. With sufficiently slow cooling, all the material passes into the solid state by the crystallizing of the several minerals in succession. This does not mean that two or more minerals may not be forming at the same time, but it means that some minerals may be crystallized out while the surrounding material is still fluid. In most igneous rocks, nearly perfect crystals of certain minerals are common, while other minerals, crystallizing later, adapt themselves to the space left between older crystals. This conception is supported by the fact that some lavas, while still in the fluid condition, contain well-formed crystals, very much as water in certain conditions may be filled with crystals of ice.

*Temperature of lava.* Accurate determinations of the temperatures of liquid lavas have not been made; but it is clear from the white heat of some lavas that their temperatures are appreciably above the melting-point. This is also a necessary inference from the length of time lavas remain fluid, in spite of its contact with cooler rock, through its miles of ascent. From various facts it is probably safe to assume that the original temperatures of lavas as they rise to the surface are in some cases considerably above 2,000° Fahr. (1,093° C.). Even such a temperature must be somewhat below the original temperature of the lava, because some heat must be lost in rising, both by contact with the cooler rocks through which it rises, and by the expansion of the gases within them.

*Depth of source.* Attempts have been made to determine the depth from which lavas rise, by calculations based on the earthquake tremors accompanying eruptions; but such calculations really tell very little concerning the true point of origin of the lava. At most they probably tell merely where the ascending lavas begin to *rupture* the rock through which they pass, and rupture may not be possible below the zone of fracture, which is probably not more than eleven miles deep.[1] In the zone of flowage below, where the pressure is too great to permit fracture, the lava not improbably makes its way by some boring or fluxing process, which might not be capable of giving rise to seismic tremors. The tremors perhaps com-

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pel us to place the beginning of movement of lava *at least as low as the bottom of the fracture zone*, but they probably offer no sufficient ground for limiting the lava's origin to this or any other specific depth.

*Volcanic gases.* One of the most distinctive features of volcanoes is the explosive action arising from the gases and vapors pent up in the lava. Lavas in the interior, under high pressure, contain much gas, and as they rise and the pressure is relieved, some of these gases escape from the hot liquid. In those cases in which the eruption is quiet, the escape of the gases is but partial while the lava is in the crater, and much gas remains to be given off after the lava has been extruded and is about to congeal. The gases are then given off slowly and quietly. If, however, the lava is surcharged with gases, and if their escape is retarded by the viscosity of the lava, they gather in large vesicles or bubbles in the lava in the throat of the volcano, and on coming to the surface explode, hurling the enveloping lava upwards and outwards. The violence of the explosion reduces a portion of the lava to the fineness of dust,— the "ash" and "smoke" of the volcano.

The causes of the differences of gas action in different volcanoes are undetermined, but the following suggestions may point to a part of the truth: (1) Some lavas contain more gases than others, and hence are predisposed to be more explosive; (2) some are more viscous than others and hence hold the gases more tenaciously until they accumulate and acquire explosive force, while the more liquid lavas allow their gases to escape more freely; (3) probably a main occasion of violent explosions lies in the fact that the lavas have begun to crystallize while yet in the volcano. When crystals form in the magma (lava), they exclude the gases which were in the substance from which they are developed, and this excluded gas overcharges the remainder of the lava. This view is supported by the fact that the pumice and ash of such extraordinary eruptions as those of Krakatoa and Pelée contain many small crystals which had formed before the explosion took place. Incipient crystallization does not, however, appear to be a universal accompaniment of explosive action.

Igneous rocks contain gases in large quantities.[1] When the lavas lodge underground without free communication with the surface, there is reason to think that they retain a larger percentage of their original gases than the lavas which are exposed freely at the surface. At any rate, deep intrusive rocks contain notable quantities of gases. Recent surface lavas also contain gases of similar kinds, but not in equal amount, so far as available analyses show.

One of the outstanding problems of geology is to determine (a) how far the material of the gases had the same origin as the material of the lavas, and (b) how far the material for the gases penetrated from the surface. The peculiar proportions of the rock-gases, among which hydrogen and carbon dioxide greatly preponderate, seem to imply that they are not derived chiefly from surface waters or the atmosphere; they appear to be original constituents of the rocks in the main, and when given forth they appear to constitute real additions to the atmosphere.

## THE CAUSE OF VULCANISM

The fundamental explanation of volcanic phenomena is wrapped up in the origin of the earth, for the conditions which the earth in-

[1] Rollin T. Chamberlin, Gases in Rocks, Carnegie Institution, 1908.

herited from its birth are doubtless leading factors in the explanation of vulcanism.[1] The explanation includes (1) the origin of lavas, and (2) the forces by which they are expelled.

The current explanations of vulcanism fall into two general classes: (1) those which assume that lavas are residual portions of an original molten mass, and (2) those which assign lavas to the local liquefaction of rock. The first of these views prevailed formerly, but it encounters grave difficulties because of the independent action of adjacent vents. When lava columns vary thousands of feet in height on the same mountain mass, as in the Hawaii volcanoes, even a resort to the hypothesis of local residual reservoirs is unsatisfactory.

Another view which has had much currency supposes that *surface water and its absorbed gases penetrate to heated rock* and are absorbed by it, rendering the whole liquid, and that the lava thus formed is forced to the surface. It does not appear, however, that surface water penetrates below the zone of fracture, and hence is far from reaching highly-heated rocks. *Relief of pressure* lowers the melting point of rock, and when felt by rocks already hotter than their melting temperatures at lowered pressures, has been held to be a possible cause of vulcanism. The necessary relief of pressure is assigned to faulting and denudation; but many volcanoes are located in the bottom of the ocean, where denudation does not take place, and faulting that would give relief of pressure is not always related to vulcanism in any clear way. *Melting by crushing* has been suggested, but in the deeper parts, crushing involves increase of pressure, which opposes melting. *Sinking to the zone of high temperature* under the weight of accumulated sediments, is also assigned as a cause of melting, but there is very little sedimentation in the ocean far from land where many volcanoes are situated.

If the earth grew up by slow accessions of matter, and if its interior heat is due chiefly to the internal *compression* resulting from growth, the distribution of internal temperature would be such that, with like conductivity, the flow of heat from the deep interior to a thick outer zone (about 1/5 of the radius) of the earth would be greater than the loss from this zone to the superficial shell. The deeper parts of the outer zone might thus rise in temperature. This zone is, under this view, supposed to be composed of various

[1] For fuller statement see the authors' larger work, Vol. I, pp. 395–607, Vol. II, pp. 99–106, 116–118, 120, 130.

kinds of matter, mixed as they happened to fall in. If its temperature rises, the fusion-points of some of its constituents will be reached sooner than those of others. A fusion or solution of the more soluble portions may thus take place while the rest of the rock remains solid. The gases and volatile constituents in the original material would obviously unite with the liquid part. With continued rise of temperature, the liquefaction would extend itself until adjacent pockets or threads of lava united, and the lighter portions of the fluid would be forced upward and would work their way toward the surface by fusing and fluxing.

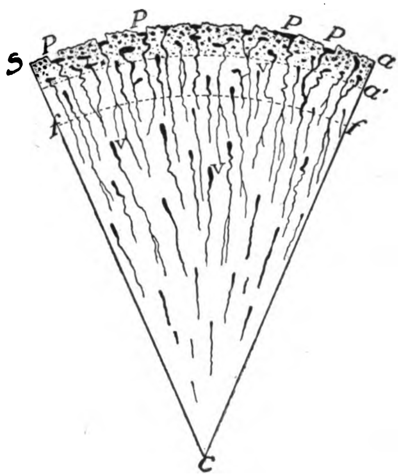



Fig. 233. Ideal section of a portion of the early earth, illustrating its assigned modes of vulcanism. *C*, center; *S*, surface; *a-a'*, fragmental zone; *a'-f*, zone of continuous rock below melting temperature at the surface; *ff-c*, interior portion whose temperatures rise from the surface melting-point at *f-f* to a maximum at *C;* *V*, *V*, threads or tongues of molten rock rising from the interior to various levels, many of these lodging within the fragmental zone as tongues, batholiths, etc.; *PPP*, explosion pits formed by volcanic gases derived from tongues of lava below.

As the lavas rise, the pressure on them becomes less, and hence the temperature necessary for liquefaction gradually falls, leaving them a constantly renewed margin of temperature available for melting their way through the upper horizons. Thus it is conceived that these fusible and fluxing selections from the middle zone might thread their way up to the zone of fracture, and thence, taking advantage of fissures and cracks, reach the surface (Fig. 233). It is conceived that such liquefaction and extrusion would carry the excess of temperature received by the lower part of the outer zone toward the surface, or even out to it. The outward movement of the lava would tend to lower the temperature below, forestalling general liquefaction, and keeping the zone as a whole, solid. The independence of volcanoes is assigned to the independence of the liquid threads that work their way to the surface. Nothing like a reservoir or molten lake enters into the conception. The prolonged

action of volcanoes is attributed to the slow feeding of the liquid threads from the middle zone, which is liquefied in spots only. The frequent pauses in volcanic action are assigned to temporary deficiencies of supply, and the renewals to the gathering of new supplies after a sufficient lapse of time. The distribution of volcanoes in essentially all latitudes and longitudes is assigned to the general nature of the cause. The special surface distribution is assumed to be influenced, though not altogether controlled, by the favorable or unfavorable conditions for escape of lava to the surface. The persistence of volcanic action in time is attributed to the magnitude of the interior source, to its deep-seated position, and to the slowness of conduction of heat from the earth's interior. The force of expulsion is found in the stress-differences in the interior, particularly the periodic tidal stresses, and in the slow pressure brought to bear on the slender threads of liquid by the creep of the adjacent rock. The violent explosions are due to the included gases, of which steam is chief. Little efficiency is assigned to surface-waters, and that little is regarded as secondary and incidental. The true volcanic gases are regarded as coming from the deep interior, and as being, after expulsion, accessions to the atmosphere and hydrosphere. The standing of the lavas in volcanic ducts for hundreds and even thousands of years with only little outflow, as in some of the best-known volcanoes, is regarded as an exhibition of an approximate equilibrium between the hydrostatic pressure of the deep-penetrating column of lava and the flowage-tendency of the rock-walls, the outflow being also conditioned on the slow supply below, and on the periodic stress-differences of the interior.

For the present, volcanic hypotheses must be left to work out their own destiny, serving in the meantime as stimulants of research. All but the last have been long under consideration. The recent discovery of the heating effects of radio-activity has given rise to the hypothesis that the origin of lavas is due to this cause. It seems clear that this must at least be a cooperative agency. It is too early in the new investigation to decide whether it can wisely be regarded as the sole cause or even an essential one.

**How lava reaches the surface.** All views that locate the origin of the lavas deep in the earth must face the difficulty of the passage of lava through rock below the fracture zone. Near the surface, the lavas usually take advantage of bedding-planes, or of fissures already existing, or made by themselves. There is little evidence

that they bore their way through the zone of fracture. In the denser and warmer zone below, the alternatives seem to be (1) mechanical penetration without fracture, or (2) melting or fluxing. As rocks "flow" in this zone by differential pressure without rupture, an included liquid mass may perhaps be forced to flow through the zone by differential pressure. Lava probably fuses or fluxes its way, under pressure, through the rock below the zone of fracture. In this it may be supposed to be assisted by its gases, by the selective nature of its fluxing, by its exceedingly high temperature if it comes from very great depths, and by the stress-differences which attend tidal strains in the deep interior. In ascending, the lava would be invading regions of lesser pressure and lower melting-point. It would therefore have heat in excess of the local melting temperature, until it reached the cool rock. From that point on, the rising lava must constantly lose temperature by contact with cool rocks. If its excess of temperature is insufficient to enable it to reach the zone of fracture, the ascending column is arrested and becomes *plutonic* rock. If it suffices to reach the zone of fracture, advantage may be taken thereafter of fissures, and the problem of further ascent probably becomes chiefly one of hydrostatic pressure, in which the ascent of the lava-column is favored by its high temperature and its included gases. The hydrostatic contest is here between the lava-column *measured to its extreme base*, and the adjacent rock-columns *measured to the same extreme depth*. The result is, therefore, not necessarily dependent on the flowage of the outer rocks, but may be essentially or wholly dependent on the deep-seated flowage of the rock of the lower horizons. The ascending column may reach hydrostatic equilibrium before it reaches the surface, and then form intrusions of various sorts, or it may find equilibrium only by coming to the surface.

*References.* C. E. Dutton, Hawaiian Volcanoes, Fourth Ann. Rept., U. S. Geol. Surv., 1883. Judd, Volcanoes, 1881; J. D. Dana, Characteristics of Volcanoes, 1890. A. Geikie, Ancient Volcanoes of Great Britain, 1897. I. C. Russell, Volcanoes of North America, 1897. T. G. Bonney, Volcanoes, Their Structure and Significance, 1899. A. Heilprin, Mont Pelée and the Tragedy of Martinique, 1903. Accounts of same volcanoes in the Nat'l. Geog. Mag., Vol. XIII, 1902 (Russell, Hill, Hovey, Diller, and Hildebrand).

*Map work.* See Plates CLV to CLXIV, of Professional Paper 60, U. S. Geol. Surv. and Exercise XVI, in Interpretation of Topographic Maps.

# CHAPTER X

## MATERIALS OF THE EARTH AND THEIR ARRANGEMENT

The general constitution of the lithosphere has been referred to already (p. 7), but we are now to study in more detail the nature, the arrangement, and the history of the rocks. The igneous rocks will be considered first.

### IGNEOUS ROCKS

**Appearance at the surface.** The preceding chapter has acquainted us with the fact that some igneous rocks were extruded either from volcanoes or from fissures, and that extrusive rocks include both lava flows and pyroclastic materials. Under proper conditions, extruded rocks may be buried later beneath sediments, or may be worn away by erosion. It follows that only a part of the igneous rocks extruded in the past, and especially those of relatively recent times, remain at the surface.

By removing the overlying rocks, erosion exposes the intruded rocks of dikes, sills, laccoliths, batholiths (p. 228), etc., and a considerable part of all accessible igneous rock is now at the surface because the rocks which overlay it have been worn away. The great areas of granite in Canada, and the long axes of many of our western mountains, are examples. Extruded igneous rock which has been buried, also is subject to subsequent exposure by the wasting away of its cover.

**Structural features of igneous rocks.** The names applied to the principal forms of igneous intrusions imply certain large structural features; but igneous rocks have certain other structural features which distinguish them from other rocks. Thus the rock of laccoliths, bysmaliths, and batholiths is generally *massive*. This term means not simply that the rock occurs in large bodies, but that the rock has no distinct *cleavage*. It is not in beds, and it is not schistose. Sills and some extrusions of lava take on the form of *sheets*. Where one extrusive sheet of lava overlies another, the succession of sheets has some resemblance to stratified rock; but

the rock of the individual sheets shows little indication of arrangement in layers. Some extruded rock has a structure developed by the flow of the lava after it had become stiff from cooling. This

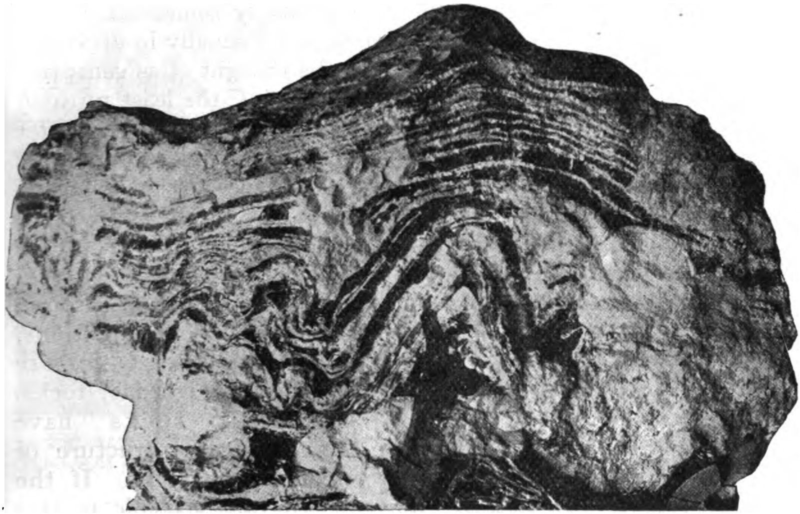


Fig. 234. Flow structure in volcanic glass. About half natural size. (Photo. by Church.)

Fig. 235. Columnar structure in igneous rock. Giant's Causeway.

is known as *flow structure* (Fig. 234). On cooling, some lavas develop *columnar structure* (Fig. 235), the columns being roughly perpendicular to the surface of cooling.

The explanation of the columns is probably somewhat as follows: The surface of the lava contracts about equally in all directions on cooling. The contraction may be thought of as centering about equidistant points. About a given point, the least number of cracks which will relieve the tension in all directions is three (*a*, Fig. 236, *A*). If these radiate symmetrically from a point, the angle between any two is 120°, the angle of the hexagonal prism. Similar radiating cracks from other centers (*b*, *c*, etc.) complete the columns (Fig. 236, *B*). A five-sided column would arise from the failure of cracks to develop about one of the points.

Igneous rocks are affected by cracks or *joints*, which run through them in various directions, but this is not a feature peculiar to igneous rocks. Pyroclastic rocks have somewhat the structure of sedimentary rocks. If the fragmental volcanic matter accumulates on the surface of the land, it may lack distinct stratification; but if it falls or is washed into water, it may be assorted and stratified. In this case it is distinguished from other clastic rock by its constitution.

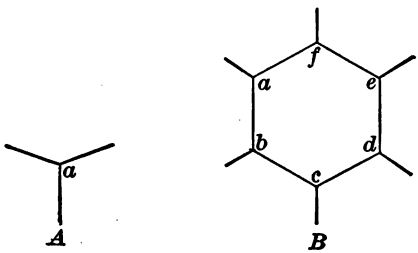



Fig. 236. Diagrams to illustrate the formation of columns of basalt: *A*, the first stage in the development of a hexagonal column. *B*, the completion of a hexagonal column.

**Textural features.** Most *igneous rocks* are made up of *interlocking crystals* of different sorts. These crystals may be so small that they are not distinguished readily by the eye, or they may be so large as to be seen easily, or some may be large and some small. If they are large enough to be distinct to the eye even without close scrutiny, the rock is coarsely crystalline. All such rocks may be called *phanerites*. In phanerites, the interlocking of the crystals is evident (Fig. 237). If the crystals are so small as not to be seen readily by the eye, the rock is *aphanite*. In all igneous rocks, the crystals are of somewhat unequal size; but in some, there are certain crystals, usually of some one mineral, which are so much larger than the others as to be conspicuous. The rock is then *porphyritic* (Fig. 238). The smaller

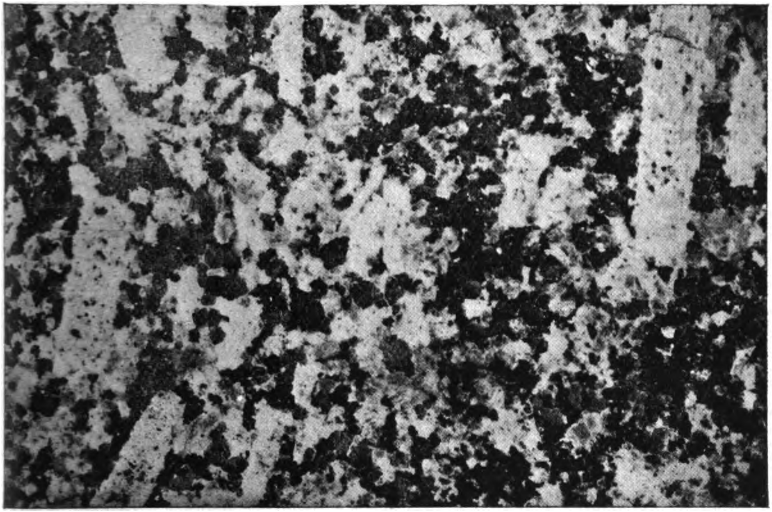


Fig. 237. Granitic rock, about half natural size. The white patches represent crystals of one or two kinds of mineral; the dark parts represent crystals of others.

crystals in which the larger ones are set may be so small as not to be readily distinguished (aphanitic), or they may be visible separately (phaneritic).

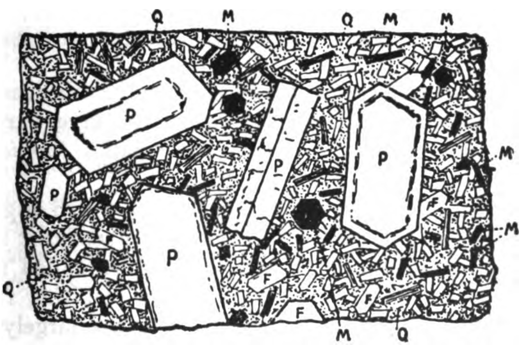



Fig. 238. Porphyritic texture. pp = phenocrysts of feldspar. The smaller crystals are of feldspar, mica, and quartz. (Watts.)

Some igneous rock is, in reality, volcanic glass. Volcanic glass (*obsidian*) is one phase of solidified lava. It is formed when the liquid lava solidifies quickly, before the crystals have time to grow. Some igneous rock is made up partly of glass and partly of crystals, and between the rock which is all glass and that which is all crystals there are all gradations. Whether lava becomes glassy or crystalline on hardening, or whether it is partly the one and partly

the other, depends on the conditions under which it solidifies. All liquid lava contains the materials out of which crystals may be formed, under proper conditions.

Glassy and partly glassy rock may be compact or porous. Porous rock of the type shown in Fig. 239 is called *scoriaceous.*

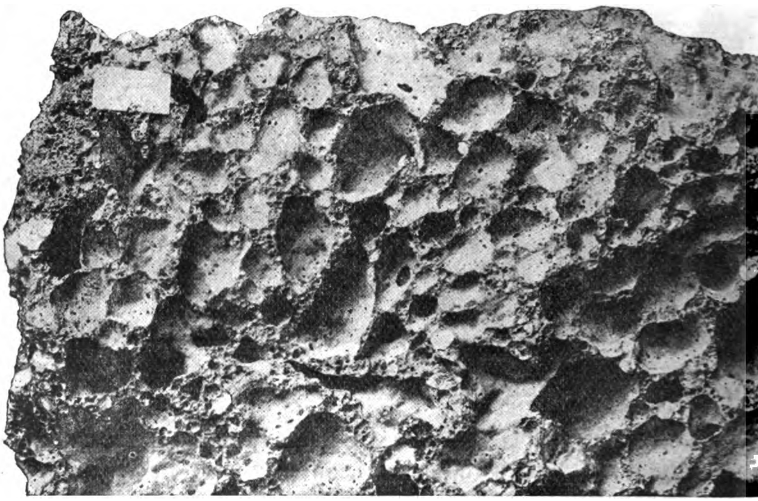


Fig. 239. Scoriaceous texture. About 4/5 natural size. (Photo. by Church.)

Rock of this sort is really lava froth, solidified. The pores are the spaces occupied by gases when the lava hardened. Some of the bubbles were large and some small. *Pumice* is porous volcanic glass, the pores being small.

Besides these varieties of texture which originate as lava hardens, there are the textures peculiar to *pyroclastic rocks.* When quantities of *volcanic dust,* etc. (sometimes called *volcanic ash*), become coherent, as by cementation, the resulting rock is called *tuff* (or *volcanic tufa*). If the constituents are largely coarse, the resulting rock is *volcanic agglomerate.*

**Liquid lava** (=*liquid glass*). Liquid lava is essentially fluid glass. It is analogous to common glass, which is a silicate of potash, soda, or other base, except that manufactured glass is relatively free from iron and other coloring substances which abound in lavas, rendering them dark and more or less opaque. Lavas, too, are

usually mixtures of several silicates, while manufactured glasses consist of only one, or at most a few. Furnace slag is essentially an artificial lava.

**Solidification and crystallization.** When lava is cooled quickly, its components solidify essentially as they were in the liquid; for there is no time for the molecules of one kind to come together in regular systematic order, as is necessary to form crystals. In a thick viscid liquid, the arrangement of molecules into definite crystal forms takes place slowly. Because of this slowness, the solidification of the lava may catch the process of crystallization at any stage. This is why some igneous rocks are glassy (cooled quickly), some partly glassy (cooled less quickly), and some wholly crystalline. In general, *the slower their growth, the larger the crystals.*

**Stages of crystallization.** Eruptions take place intermittently, and the lava beneath the surface may be cooling during the intervals between eruptions. After a certain stage of partial crystallization has been reached during such time of quiet, a new eruption may shift the whole mass of lava into new surroundings, and a second phase of solidification may be added to the first. The rock may then show two phases of crystallization: (1) large crystals of the kind or kinds developed during the first stage of slow subterranean cooling; and (2) small crystals or glass developed during the more rapid cooling of the second stage. The result is large crystals set in a matrix of small crystals or of glass. This is perhaps one way in which *porphyry* is formed.

## *Composition of Igneous Rocks*

Nearly all the chemical elements are found in igneous rocks, though but few of them are abundant. These few are regarded as the essential constituents, while the rarer substances are regarded as incidental. The relative amounts of the more abundant elements in the crust of the earth, as nearly as now known, are shown in the following table:

| Element | Symbol | Per cent in the Solid Crust |
|---|---|---|
| Oxygen | (O) | 47.02 |
| Silicon | (Si) | 28.06 |
| Aluminum | (Al) | 8.16 |
| Iron | (Fe) | 4.64 |
| Calcium | (Ca) | 3.50 |
| Sodium | (Na) | 2.63 |
| Magnesium | (Mg) | 2.62 |

| | | |
|---|---|---|
| Potassium | (K) | 2.32 |
| Titanium | (Ti) | .41 |
| Hydrogen | (H) | .17 |
| Carbon | (C) | .12 |
| Phosphorus | (P) | .09 |
| Manganese | (Mn) | .07 |
| Sulphur | (S) | .07 |

It will be seen that only eight of the elements enter into the earth's crust to the extent of one per cent, and no other one reaches half of one per cent. Many elements that are of great importance in the affairs of men occur in quantities too small to be estimated in percentages. The precious metals, such as platinum, gold, and silver, and even some of the more common ones, as lead, zinc, and copper, are of little importance *quantitatively.*

*Union of elements.* For present purposes we may neglect all but the first eight of the elements mentioned above. Out of these elements come various chemical combinations when the lava solidifies; out of these combinations come the various minerals; and from combinations of minerals come various kinds of rocks. The union of oxygen with the other seven elements may be taken as a fundamental step in this series of combinations. The result is the following oxides: Silica ($SiO_2$), alumina ($Al_2O_3$), the ferrous, ferric, and magnetic oxides (FeO, $Fe_2O_3$, and $Fe_2O_3$), magnesia (MgO), calcium oxide (lime) (CaO), soda ($Na_2O$), and potash ($K_2O$). The oxygen sometimes unites in proportions different from those here given, but exceptions may be neglected here.

Of these nine oxides, silica acts as an acid, or more strictly as an acid anhydride. All the rest except the magnetic oxide of iron, and sometimes the oxide of aluminum, act as basic oxides. The proportion of silica in igneous rocks is so significant that all such rocks are sometimes grouped into three classes, as follows: those with more than 65% of silica are *acidic;* those containing 55 to 65%, *intermediate;* and those containing less than 55%, *basic.*

The union of silica ($SiO_2$) and lime (CaO) forms calcium silicate, $CaO,SiO_2$, or $CaSiO_3$. The union of silica and magnesia forms magnesium silicate, $MgO,SiO_2$, or $MgSiO_3$. Corresponding unions of silica and the other oxides named, give rise to other silicates.

*Formation of minerals.* Since but one of the leading oxides (silica) that abound in the average lava plays the part of an acid, a very simple conception of the general nature of igneous rocks may be reached by noting that they are composed mostly of silicates of the eight leading basic oxide—those of alumina, potash, soda, lime, magnesia, and iron. This general idea represents a most important truth; but in its use we must not forget that there are many exceptions. Sulphur, phosphorus, chlorine, and other elements unite with the bases to form sulphates, sulphides, phosphates, phosphides, chlorides, etc. So also there are many minor bases that form silicates; and these minor bases unite with minor acids to form many of the rarer minerals. Again, there are native metals in some igneous rocks; but altogether these minor compounds hardly reach more than one or two per cent of the whole.

There are two exceptions of more importance. In the liquid lava the acid and basic elements are not always evenly matched. When there is an *excess of silica*, a portion remains free and takes the form of *quartz* ($SiO_2$). If there is an *excess of the basic oxides*, the weakest one is usually left out of the combination. This is commonly an *iron oxide* ($Fe_3O_4$), called *magnetite*. It is a singular fact that quartz forms in some cases where there is no excess of silica, and magnetite where there is no excess of base. Quartz (free acid anhydride) and magnetite (free basic oxide) may occur in the same rock. The explanation of this is yet to be found. The oxides of silicon and iron form rather important exceptions to the general statement that igneous rocks are made up mostly of silicates; but, thus qualified, the statement expresses the essential truth.

But here simplicity ends, and the sources of complexity are several. In the first place, silica unites with the bases in different ratios, and thus gives rise to *uni-silicates* or *ortho-silicates* (ratio of oxygen of base to oxygen of silica, 1:1), *sub-silicates* (the above ratio more than 1), *bisilicates* (ratio 1:2), *tri-silicates* or *poly-silicates* (ratio 1:3 or higher), etc. All the bases are not known to combine in all these ways, but many do in more than one.

If the silica united with each of the bases one by one, the results would still remain comparatively simple; but instead, it may unite with two or more at the same time. Thus we may have an aluminum-calcium silicate. Not only this, but the different silicates may crystallize together in the same mineral, so that a crystal may be made up of alternating layers of different silicates. As such alternations are not governed by any known mathematical law, there is no determinate limit to the number of combinations that may arise.

As a result of all this fertility of combination, the total number of siliceous minerals in igneous rocks is large. Geology deals with these minerals as constituents of the earth, but only a few of them are so abundant as to require special notice here. It may be remarked also that, as they occur in the rocks, only a few of them can be identified by simple inspection, partly because some of them look much alike, and partly because many of the crystals are minute.

**Summary of salient facts.** The salient facts are, (1) that out of the 70-odd chemical elements now known in the earth, eight form the chief part of it; (2) that one of these elements uniting with the rest forms nine leading oxides; (3) that one of these oxides acts as an acid and the rest as bases; (4) that by their combination they form a series of silicates of which a few are easily chief; (5) that these silicates crystallize into a multitude of minerals of which again a few are chief; and (6) that these minerals are aggregated in various ways to form rocks. Possessed of these leading ideas, we are prepared to turn to the consideration of some of the conditions under which these combinations take place in the formation of rocks from liquid magmas.

**Principal minerals of igneous rocks.** A few minerals make up the mass of igneous rocks. These few are *quartz*, the *feldspars*, the *ferro-magnesian* minerals (amphiboles, pyroxenes, micas), and the

*iron oxides.* These minerals are described briefly below. Some of them occur in sedimentary and metamorphic works, as well as in igneous rocks.

*Quartz.* $SiO_2$; H. 7; Sp. gr. 2.65. A mineral of very widespread occurrence. It is found not only in igneous rocks, but in veins and cavities in other sorts of rock, as nodules and concretions in limestones, and is the most abundant constituent of sands, sandstones, and quartzites.

Quartz is a very hard mineral; that is, it cannot be scratched with steel and it will scratch glass. It is said to have conchoidal fracture; that is, it breaks like glass, without any distinct tendency to break along parallel planes. In igneous rocks, quartz usually looks rather dark and glassy by contrast with the lighter colored, less transparent minerals with which it is commonly associated. Some quartz has a sort of greasy or oily look because of its comparatively high luster. In veins and cavity fillings it may occur, (1) as 6-sided crystals capped by pyramid-like forms. The crystals may be so closely spaced that only the pyramid-like forms can be seen; (2) as a sort of hummocky crust with a waxy luster (chalcedony), or (3) as a series of bands of variegated color (agate). As concretions in limestone it may have a variety of colors, but is usually between white and dark grey, in some cases nearly black. Concretions are usually irregular in form, and contain a considerable proportion of impurities, but can be recognized by the hardness of a freshly broken surface.

Some of the less common varieties are used as semi-precious stones; for example, amethyst, cairngorm, rose quartz, jasper, prase, cat's-eye, and agate. True onyx is also a variety of quartz.

*The feldspars.* H. 6; Sp. gr. 2.5–2.6.

*Orthoclase*, Potassium aluminum silicate

*Plagioclase* { Sodium aluminum silicate<br>Calcium aluminum silicate

Feldspars are abundant in igneous rocks and their metamorphic products, but are not found abundantly in other rocks. Feldspars are not so hard as quartz, but cannot be scratched by any but the very hardest steel. They have good cleavage; that is, they have a strong tendency to break along parallel plane surfaces. This can be detected by holding a freshly broken surface to the light so that a reflection is seen. If the whole surface of a crystal seems to reflect the light when the fragment is held in a given position, it is usually due to the cleavage of the mineral. Feldspars are commonly the dominant light colored constituents of igneous rocks, but they range in color through white, buff, pink, red, and grey, and a comparatively rare variety is green.

It is not always easy to distinguish orthoclase, $KAlSi_3O_8$, from plagioclase, a mixture of $NaAlSi_3O_8$ and $CaAl_2Si_2O_8$; but the cleavage faces of some plagioclase crystals show distinct parallel striations, almost as true as if made by a ruling engine. These are never present in orthoclase. The dark, dull or waxy looking feldspars are more likely to be plagioclase, while buff or pink feldspars are more likely to be orthoclase; but such distinctions are too uncertain to be used with great assurance.

Some of the rarer feldspars are used as semi-precious stones. Among these are Amazonstone, sunstone, moonstone, peristerite and labradorite.

*Amphiboles and pyroxenes.* Complex silicates, usually containing iron, lime, and magnesia. H. 5–6; Sp. gr. 2.8–3.6. The amphiboles and pyroxenes occur chiefly in igneous and metamorphic rocks, in some of which they are the most abundant dark colored constituents.

They are hard minerals, that is, can be scratched by steel with difficulty. The commoner ones are black, greenish black or brown. *Hornblende* is the most important of the amphiboles, and *augite* of the pyroxenes. These minerals resemble eachother rather closely, and in very small crystals it is in some cases difficult to distinguish them. The most notable difference is in the cleavage. Hornblende cleaves in two directions at an angle of 124° (and 56°) from each other, while in augite the two cleavage directions are nearly perpendicular to eachother. Most hornblende has a jet-like luster, while augite is more likely to be dull, and is likely to be coated with rust on weathered surfaces. Another amphibole of importance is *actinolite*, which occurs only in metamorphic rocks and is easily recognized by its long, slender, needle-like crystals, which have a diamond-shaped cross-section and are usually bright green in color. With the exception of *bronzite*, which is distinguished by its brown color, the other important pyroxenes cannot be distinguished readily from augite.

*The micas.* Complex hydrated silicates. H. 2; Sp. gr. 2.76–3. The common micas occur in igneous and metamorphic rocks and to a small extent as minute flakes in some sandstones and shales. The commonest micas are *muscovite*, which is white, greenish or yellowish brown, and *biotite*, which is dark brown or black. They are very soft, that is they can be scratched with the thumb-nail, and have a conspicuously good cleavage — so good that they may be split into sheets thinner than the thinnest paper. These thin sheets or flakes are very elastic and tough. In metamorphic rocks the plates are roughly parallel, and this results in the characteristic schistose appearance of many such rocks. Microscopic flakes of mica, arranged parallel to one another are responsible for the cleavage of slates. The only simple means of distinguishing between muscovite and biotite is the color.

*Olivine.* $(FeMg)_2SiO_4$; H. 6.5–7; Sp. gr. 3.3–3.5. Olivine occurs in the more basic igneous rocks, that is, those that are comparatively low in silica, especially those that are rich in ferromagnesian minerals. Olivine also occurs in metamorphic rocks, especially metamorphosed dolomitic limestones. It is a very hard mineral, and has conchoidal fracture. In color it is yellowish green, varying somewhat according to the amount of iron present. It is usually transparent, and has a vitreous luster. It commonly occurs in granular aggregates which contain some pyroxene, but is found also in crystals in some dark colored igneous rocks. A variety used as a gem is called *peridot. Chrysolite* is another name applied to olivine.

*The iron oxides.*

Hematite, $Fe_2O_3$; H. 5.5–6.5; Sp. gr. 4.8–5.4.
Limonite, $2Fe_2O_3,3H_2O$; H. 5–5.5; Sp. gr. 3.6–4.
Magnetite, $Fe_3O_4$; H. 6; Sp. gr. 5.18.

*Hematite*[1] is the most important of the iron ores. It occurs (1) in sedimentary rocks, in some cases being the cementing material in sandstones, as in many of the red sandstones; (2) in igneous rocks as the result of weathering of the iron minerals; (3) in veins, and (4) in contact metamorphic deposits. It is mostly hard, but

[1] Turgite is here included with hematite.

shows some variation in hardness, as some specimens can be scratched by steel while others cannot. Hematite is red, dull steel blue, or black. Its most characteristic feature is the color of the streak, that is, the color of the fine powder left behind when the specimen is drawn across an unglazed porcelain plate, or powdered *very finely* in any way. The color of the streak or fine powder is dark brownish red. The pigment called Venetian red is merely very finely ground hematite, containing a small amount of clay.

*Limonite* occurs in the same sorts of situations as hematite and as an alteration product of many ore deposits containing iron sulphides. It is deposited in some bogs in sufficient quantity to be valuable as an iron ore. Chemically it is the same as iron rust. Limonite has a very wide range of hardness, from soft earthy material, to compact material which cannot be scratched with steel. In color it ranges from light yellowish brown to very dark brown — in some cases almost black. The streak is characteristically yellowish brown, no matter what color the specimen has in mass. The common pigment yellow ocher owes its color to limonite.

*Magnetite.* Magnetite occurs in igneous and metamorphic rocks, in contact metamorphic deposits, and to a limited extent in veins. It is very hard, and characteristically black in color, except on weathered surfaces, where it is usually coated with rust. The streak is black. Magnetite is most easily recognized by its magnetic properties. It is strongly attracted by a magnet, and may be magnetized. Naturally magnetized magnetite is called lodestone, and it is from this substance that our term magnet is derived. Magnetite is of comparatively little importance in America as an iron ore, but in some parts of Europe it is a very important ore mineral.

**Other important rock-forming minerals.** A few other common rock-making minerals are mentioned here, though most of them do not occur in igneous rocks, except as secondary minerals introduced subsequent to the hardening of the lava. Several of them occur in metamorphic rocks only. Calcite and dolomite occur abundantly in certain sedimentary rocks, but are secondary in igneous rocks.

*Calcite.* Calcium carbonate, $CaCO_3$. H. 3; Sp. gr. 2.72. Calcite is a mineral of very widespread occurrence. It is the chief constituent of limestones and marbles (metamorphosed limestones), and occurs as cavity fillings in many kinds of rocks. It is a very common vein mineral and occurs as an alteration product of lime silicates in many weathered igneous rocks. Calcite is rather soft; that is, while it cannot be scratched with the thumb-nail, it is scratched easily with steel. It has a very good cleavage in three directions which may give rise to rhombohedrons, that is figures like cubes, which have been compressed along one diagonal. It is recognized most readily by its behavior towards acids, which act upon it rapidly, causing an effervescence of carbon dioxide. Some other minerals effervesce similarly, but none of the very common ones show such rapid action as calcite. Transparent pieces of calcite show double refraction; that is, if a piece of transparent calcite is placed over a dot on a piece of paper, two dots may be seen distinctly. Most calcite is white or colorless, but some is colored brown, yellow, green or pink by impurities of various sorts.

*Chlorite.* A complex, hydrated silicate containing Fe and Mg. H. 2; Sp. gr 2.65–2.75. Chlorite is a secondary mica; that is, it is a mica formed by the action of weathering on certain silicates containing iron and magnesium. It occurs in metamorphic rocks, and as an alteration product in igneous rocks. It is very

soft, usually dark green or greyish green in mass, and gives a grey or greenish grey streak. Chlorite has micaceous cleavage, and the plates are mostly flexible and inelastic. The greenish color of many igneous rocks is due to the presence of chlorite formed by the alteration of pyroxenes, amphiboles, etc.

*Dolomite.* $CaMg(CO_3)_2$. H. 3.5–4; Sp. gr. 2.8. A mineral closely resembling calcite. Dolomite occurs in some of the older limestones, in some marbles, and to a small extent in veins. It is a rather soft mineral, showing a cleavage like calcite when crystals of sufficient size are seen. Some dolomitic rocks are so fine grained that the individual crystals cannot be detected without the aid of the microscope, and in such specimens no cleavage is apparent. Some dolomite crystals exhibit peculiarly curved faces, which are rare in calcite. Most dolomite is milky white, brownish, or pink, but it varies greatly in color with impurities of various sorts. It is most easily distinguished from calcite by its behavior with dilute acids. Calcite effervesces vigorously even in quite dilute acids, while dolomite is only very feebly attacked by such acids.

*Garnet.* A complex silicate, different varieties having different composition. H. 6.5–7.5; Sp. gr. 3.15–4.3.

Garnet is rarely found outside of metamorphic rocks, in which it is in some instances so abundant as to be the chief constituent. It is a very hard mineral — about as hard as quartz; but when it has been exposed to weathering for a long time it may in some cases be scratched with steel. Garnet has no cleavage, but breaks with conchoidal fracture like glass or quartz. In color most garnets are red or brown, but other colors, as pink and green, are known. Garnet has rather high specific gravity compared with the rest of the common silicates. Garnet is used in large amounts as an abrasive, and to a small extent as a gem stone.

*Graphite (carbon).* H. 1–2. Sp. gr. 2.1.

Graphite is one of the crystalline modifications of carbon. It occurs in metamorphic rocks — mostly in metamorphosed sedimentary rocks. It is very soft and has a marked greasy feel, like that of talc. It is black, and will mark paper with a black streak, a property of which use is made in common lead pencils. Graphite also is used in the manufacture of crucibles, as a lubricant, and as an adulterant.

*Gypsum.* Hydrated calcium sulphate; $CaSO_4,2H_2O$; H. 2; Sp. gr. 2.3.

Gypsum occurs in beds among other sedimentary rocks, in some places as a residue from the evaporation of saline lakes, and in crystals scattered through shales. It occurs sparingly in veins. It is a very soft mineral and commonly has a very good cleavage, resembling mica, except that the thin leaves are not elastic nor strong like those of mica. It has not the greasy feel characteristic of talc. A number of varieties of gypsum are recognized. *Selenite*, the common variety of gypsum, has been described above. *Satin spar* is a variety that has a fibrous structure, and a bright satin-like luster. *Alabaster* is white massive gypsum; that is, gypsum which is made up of minute crystals which cannot be readily distinguished as individual crystals. Gypsum is characteristically white, but may be reddish, brownish or gray when it is impure. Gypsum is largely used in the manufacture of various sorts of plaster. Alabaster of high grade is sometimes used for ornamental vases, etc.

*Kaolin.* A hydrous aluminum silicate. H. 2–2½; Sp. gr. 2.6. Kaolin occurs in igneous rocks as an alteration produce of feldspars, and in sedimentary rocks. Shales and clays are made up largely of kaolin, and it is present in varying

quantities in other sedimentary rocks. It is a very soft mineral, and when free from grit usually has a soapy feel, but differs from talc in that it becomes plastic if ground up and moistened with water. Kaolin is earthy in appearance, and breaks like an earthy substance. No cleavage is apparent, because the mineral is not commonly crystallized, and when crystallized the individual crystals are too small to show cleavage without the aid of the microscope. Its color is nearly white when pure, but more commonly is brown, or bluish gray, according to the impurities it contains.

*Pyrite.* $FeS_2$. H. 6–6.5; Sp. gr. 5.0. Pyrite occurs in minute crystals in igneous rocks, in large masses in some veins and in metamorphic rocks, and is not uncommon in limestones, sandstones and shales. It is abundant in some coal beds and is the source of the sulphurous odor of coal smoke. Pyrite is very hard, has a bright metallic luster resembling that of light colored brass, but its streak is black. Crystals of pyrite may be cubes, octahedrons, or more complex forms; slightly deformed cubes with striated faces are the most common. When exposed to weathering, pyrite rusts — that is changes to limonite. If the original form of the pyrite crystal is retained by the limonite, it is called a ***pseudomorph.*** Pyrite is used in the manufacture of sulphuric acid, and to a very small extent as a source of low-grade iron.

*Serpentine.* Hydrated silicate of magnesium. H. 4; Sp. gr. 2.5–2.6. Serpentine occurs chiefly in metamorphic rocks, and as an alteration product in basic igneous rocks. Serpentine has a greasy feel, but less marked than that of talc. Most of it is yellowish green or yellow in color, but may be stained brown by iron oxides. One variety of serpentine consists of fine, closely packed, flexible fibers, called *asbestos.* Most asbestos occurs in vein-like masses in massive serpentine, the fibers running across the vein. Serpentine is used as a building stone and for interior decoration; asbestos is used in fire-proofing and in the thermal-insulation of material of various sorts.

*Talc.* A hydrous magnesium silicate. H. 1; Sp. gr. 2.75. Talc is an alteration product of magnesium silicates, especially those free from alumina, and abounds in their metamorphic products. It may occur about the mineral grains in weathered igneous rock, but occurs more abundantly in metamorphic rocks, such as soapstone and talc schist. It is very soft and has a peculiar greasy feel that usually serves as a valuable aid in identification. Some specimens show very good cleavage, resembling mica except for the fact that the thin plates are not elastic. In translucent specimens most talc is light green in color; in opaque specimens, it varies from nearly white to dark gray. Some varieties resemble kaolin (pure clay), but may be distinguished readily from it by moistening some of the finely powdered mineral; kaolin becomes plastic while talc does not.

### *Classification of Igneous Rocks*

Several features are involved in the classification of igneous rocks. Some of them have been noted already, but may be recapitulated here. All fragmental igneous rocks are ***pyroclastic***, and pyroclastic rocks may be ***tuffs***, ***agglomerates***, etc. (p. 263). Rock formed from lava without the development of crystals, is ***obsidian***, if not porous. If porous (hardened rock-froth), the rock is ***pumice***, ***scoriaceous glass***, etc. If the rock is largely glass, but partly of small crystals, it is sometimes called ***pitchstone***, because its freshly fractured surface looks like pitch or resin. When the cavities of scoriaceous rock become filled by minerals deposited from

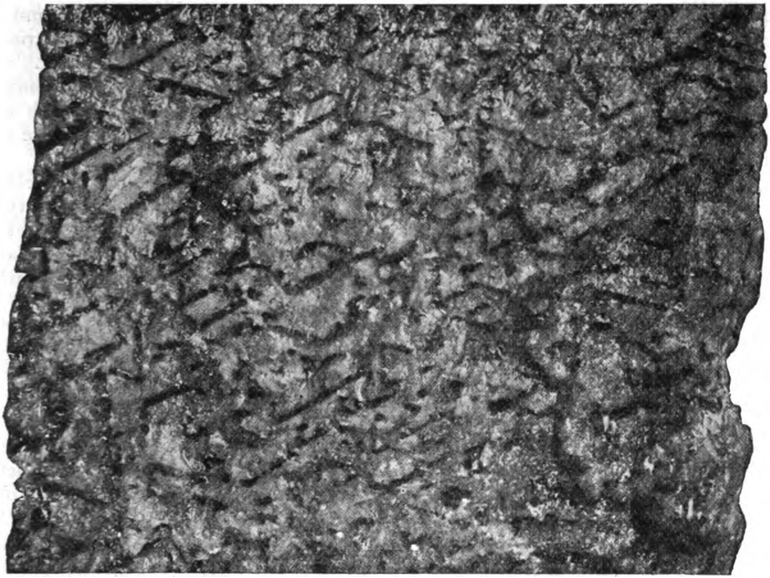


Fig. 240. Graphic granitic (or pegmatitic) texture. Nearly natural size. (Photo. by Church.)

solution, the rock becomes an *amygdaloid*. *Porphyry*, *phanerite* and *aphanite* have been defined already (p. 248). All these names are based on texture, rather than on mineralogical or chemical composition.

Most igneous rocks are wholly crystalline, and are classified on the basis of their composition. Their chemical composition determines their mineral composition, and the rocks are named according to the minerals they contain. The number of varieties of igneous rock is very large, but only a few of the more important need be mentioned here.

*The granites.* The name granite was originally used to designate a granular rock (a phanerite, p. 248), and it is still popularly and properly so used. In scientific treatises it usually has been confined to a rock composed chiefly of crystals of quartz, feldspar (especially orthoclase) (p. 254), and mica. Recently it has been proposed to give it again a more general application by including under it all phanerites composed chiefly of quartz and feldspar of any kind, with mica, hornblende, or other minerals in subordinate amount. In normal granite, the crystals are distinct and in some cases large (Fig. 237), and more or less intimately interlocked. Granites are among the most common and easily recognized of the phanerites. Their color is determined largely by the feldspar, the red and pink varieties of the mineral giving rise to red and pink granite, and the whitish varieties to gray granite. Granites vary widely from their type by the addition and substitution of other minerals. Whenever one of these replacing or accessory

minerals is abundant, its name is often prefixed, as hornblende-granite. Granite grades insensibly into other types of igneous rock, as syenite, diorite, etc. Variations also arise from the absence of one of the leading minerals.

Granites were formed from lavas rich in silica (normally 68–70%), alumina, potash, and soda, but generally poor in lime, iron, and magnesia. Granite is generally an intrusive massive rock. When rock of the composition of granite is banded, it is *gneiss*.

*Graphic granite*, composed chiefly of inter-grown crystals of quartz and feldspar, has a peculiar texture (Fig. 240). *Pegmatite* is a variety of coarsely crystalline granite composed chiefly of quartz, feldspar, and muscovite (p. 255). It occurs principally in dikes and veins associated with granitic and other similar rocks. Rock of similar texture may have the composition of syenite (syenite pegmatite), diorite (diorite pegmatite) etc.

*The syenites.* The term syenite (from Syene on the Nile, where this sort of rock occurs) is now applied to rock consisting essentially of feldspar and hornblende, with or without mica; but there is a complete gradation from granites to syenites. Syenites are richer in iron and magnesium than granites, and poorer in silica (about 58–60%). Syenites also grade into other classes of rock as do granites, and special varieties are named by similar prefixes, as augite-syenite, etc. Syenites are red or gray according to the color of the feldspar, and most of them are rather darker than granite, which they resemble. The texture of syenite is like that of granite, and its mode of occurrence the same.

*The diorites.* Diorites are rocks which crystallized from lavas having about the same amount of silica as the lavas of the syenites, but poorer in the alkalies, and richer in the earthy bases. In current usage, diorite is defined as a rock composed of an intimate mixture of crystals of hornblende and a plagioclase feldspar. It differs from syenite in having plagioclase feldspar (p. 254) instead of orthoclase. By substitutions and the addition of accessory minerals, the diorites grade toward the granites and syenites on the one hand, and toward the gabbros on the other. In color most diorites are rather darker than the gray granites.

*The gabbros.* The gabbros embrace a large group of rocks whose principal minerals are plagioclase (normally labradorite) and pyroxene (normally diallage), with magnetite or ilmenite (titanium iron oxide). Most gabbros are dark colored and rather heavy. The pearly luster of the cleavage faces of the diallage gives a peculiar sheen to a fresh surface of the rock, in many cases. Silica constitutes about 46 to 55 per cent of gabbros.

*The peridotites.* Peridotites were formed from a magma in which silica was low (39–45%), as were also alumina, lime, and the alkalies, but in which magnesia was high (35–48%). The rock consists largely of the mineral *olivine* (p. 255.) associated with pyroxene, magnetite, and other basic minerals. Little or no feldspar is present. Peridotites are much less abundant than the preceding rocks.

Closely allied with the peridotites are rocks made up largely of a single basic mineral, as *augitite*, *pyroxenite*, *hornblendite*, rocks essentially formed of the minerals augite, pyroxene, and hornblende, respectively.

*The basalts.* The term basalt is used in a somewhat comprehensive way for dark, compact, igneous rocks the crystals of which are in most cases so minute as not to be distinguished readily by the eye. The leading minerals are a plagioclase feldspar and pyroxene (usually augite), with olivine, and magnetite or ilmenite usually present. There is a considerable range in chemical composition, but the

basalts are relatively poor in silica (46–55%), and most of them in potash and soda, but rich in lime, magnesia, and iron. Basalts are classed as basic, and some are highly so. The lavas of many basaltic flows were very fluid, and spread out in thin sheets when poured out upon the surface. In cooling, basalt is prone to take on a columnar structure (p. 248). The columns of Giant's Causeway and Fingal's Cave are familiar examples.

Basalts graduate insensibly into *dolerites*, which may be regarded as basalts of coarse crystallization. *Diabase* is a rock of similar composition and ophitic texture; that is the pyroxene crystals are separated into thin plates by inter-growths of plagioclase.

**General names.** The difficulty of distinguishing many of the foregoing rocks from each other by any means available in the field, owing to the minuteness of the crystals, and to the gradation of one type of rock into another, makes it desirable to employ certain general names which will correctly express the leading character of the rock without implying a knowledge of its precise mineral composition. A convenient term of this kind is *greenstone*, which merely indicates that the ferro-magnesian minerals are prominent, and give a greenish or greenish black cast to the rock. The greenstones embrace the dolerites and basalts, and some of the gabbros and diorites, and may even extend to the peridotites and perhaps to others. Another convenient name is *trap*, which may be used for any dark, heavy igneous rock, such as basalt. The term basalt is sometimes used in much the same way.

**Varieties of rock dependent upon conditions.** From what has preceded, it is clear that the chemical nature of the liquid magma determines the mineralogical composition of the rock, if it is crystalline; but it may now be pointed out that the same lava which made a plutonic granite, might have made a porphyry, an obsidian, a pumice, or a tuff, under other conditions of solidification. The same is true of diorites, gabbros, etc.

### *A New System of Classification and Nomenclature of Igneous Rocks*

The current systems of classifying and naming rocks, if indeed they can be called systems, have grown up gradually out of earlier and cruder methods, many of which were inherited from popular usage. Most of the names and definitions came into use before modern methods of study were adopted. These systems, therefore, retain many crudities and inconsistencies, and lack adaptation to present needs and knowledge. A more adaptive and consistent classification is needed, and in response to this need, a new system of classification of igneous rocks has been offered by a group of leading American petrologists.[1] To some extent this proposed system may be extended to metamorphic crystalline rocks. The classification and nomenclature of the sedimentary rocks probably must always remain plastic, to express the various points of view which it is desirable to consider.

The proposed system includes two parts, a *field system* and a *quantitative system*, the one applicable to rocks on casual inspection, and the other only after detailed study. The field system only is here outlined.

**The proposed field system.** The proposed field names are based largely on *texture* and *color*. Mineral constituents are used for subdivisions when they can be determined easily; otherwise they are neglected.

[1] Cross, Iddings, Pirsson, and Washington. *Quantitative Classification of Igneous Rocks*. See also Johannsen, Jour. Geol. Vol. XIX (1912), p. 317.

Classifying chiefly on the basis of texture and crystallinity, there are three groups: *Phanerites,* in which all the leading mineral constituents can be seen without a lens; *aphanites,* in which at least an appreciable part of the minerals cannot be distinguished by the unaided eye; and *glasses,* in which the material is wholly or largely vitreous.

I. The *phanerites* are classified further as follows:

1. *Granites,* consisting largely of *quartz* and *feldspar* of any kind, with or without mica, hornblende, pyroxene, or other minerals. This differs from the present common use of the term granite, in not regarding mica as an essential constituent, and in not distinguishing between alkali feldspars and calcic feldspars. The term therefore includes more than formerly.

2. *Syenites,* consisting predominantly of *feldspar* of any kind, with subordinate amounts of hornblende, mica, or pyroxene, but with little or no quartz. This differs from the common usage in giving hornblende a subordinate place, and in embracing rocks with calcic feldspars.

3. *Diorites,* consisting predominantly of *hornblende* and subordinately of *feldspar* of any kind, with which there may be mica, pyroxene, or other minerals. This is nearly the present use, except that any kind of feldspar may be the subordinate mineral.

4. *Gabbros,* consisting predominantly of *pyroxene* and subordinately of *feldspar* of any kind, with or without other minerals. This nearly coincides with one of the various present uses of the term, except that the range of the feldspar is increased.

5. *Dolerites,*[1] consisting predominantly of *any ferromagnesian mineral* not distinguishable as hornblende or pyroxene, with subordinate amounts of *feldspar* of any kind, and with or without other accessory minerals. In other words, the *dolerites* (deceptive) embrace diorites and gabbros when they cannot be distinguished by the eye.

6. *Peridotites,* consisting predominantly of *olivine* and *ferromagnesian minerals without feldspar,* or with very little.

7. *Pyroxenites,* consisting essentially of pyroxene.

8. *Hornblendites,* consisting essentially of hornblende.

II. The *aphanites* may be *non-porphyritic* or *porphyritic.*

(a) Non-porphyritic aphanites, if light-colored, may be classed as *felsites;* when dark-colored, as *basalts.*

(b) The porphyritic aphanites or *porphyries,* if light-colored, are *leucophyres;* when dark-colored, *melaphyres.* They may be classified further, according to the kind of phenocryst (distinct crystal) imbedded in the aphanitic groundmass, as

*Quartz-porphyries,* or quartzophyres;
*Feldspar-porphyries,* or felspaphyres (not felsophyres);
*Hornblende-porphyries,* or hornblendophyres; and so on.

These may be subclassed by color, as

*Quartz-leucophyres,* light-colored quartz-porphyries;
*Quartz-melaphyres,* dark-colored quartz-porphyries;
*Feldspar-leucophyres;*
*Feldspar-melaphyres;* and so on.

III. The *glasses* are classified, according to color and luster, into *obsidians*

[1] Added by the authors of this work.

or *pitchstones* when dark and lustrous; *perlites* when a spheroidal fracture gives them a pearly appearance; and *pumice* when greatly inflated by included gases.

IV. *Pyroclastic rocks* are

*Tuff*, if composed of finely comminuted pyroclastic material;

*Volcanic breccia* if composed of coarse angular pyroclastic materials. *Agglomerate* is a term much used for volcanic breccia, and for similar rock whose constituents are but little rounded. If the constituents are well rounded, the rock becomes *volcanic conglomerate*.

In general discussions, it is serviceable to use the term *granitoids* in a broad generic sense, to include all crystalline rocks of the general granitoid type, including the granites, syenites, etc. In a similar broad way, *gabbroids* may be used to include the dark crystalline rocks in which the ferromagnesian minerals predominate, as the diorites, gabbros, dolerites, peridotites, etc. In this convenient and comprehensive way, two contrasted groups of igneous rocks may be designated. As the granitoids are usually acidic and the gabbroids basic, the grouping represents a broad fact of importance.

### *The Disruption of Igneous Rocks*

At the surface, igneous rocks are subject to mechanical disruption, and to chemical change which results in decay.

**Mechanical disruption.** One great agent of mechanical disruption at the surface is change of temperature. This has been discussed in Chapter II and other phases of mechanical disruption are discussed in Chapters IV and V. All mechanical disruption of igneous rock leaves the fragments essentially like the original rock in composition.

**Chemical disintegration.** Most of the silicate minerals which make up the larger part of all igneous rock are complex, chemically. Not a few of them contain as many as three or four basic elements, in union with oxygen and silicon. Substances which are complex chemically, are, as a rule, less stable than those of simple constitution. Complex silicates, such as the feldspars, micas, amphiboles, and pyroxenes tend to break up into simpler substances. Chemical changes are helped along by the oxygen, carbon dioxide ($CO_2$), and water vapor of the air, and by water after it is precipitated. Some of the simpler changes may be noted.

Oxygen may enter into combination with the iron of a silicate mineral containing iron. The iron is thus taken out of its silicate combination, and in union with the oxygen forms iron oxide, a simple and stable chemical compound. This process is *oxidation*. Oxidation affects other elements also.

Similarly, carbonic dioxide from the air may enter into combination with the base of a silicate mineral. Thus it enters into

combination with the calcium of a mineral which contains calcium, taking the latter out of its union with silica. The union of the calcium and the carbon dioxide gives rise to calcium carbonate. Magnesium and iron may be taken out in the same way, forming magnesium carbonate and iron carbonate, respectively. This process is called *carbonation*, and the carbonates thus formed are simple

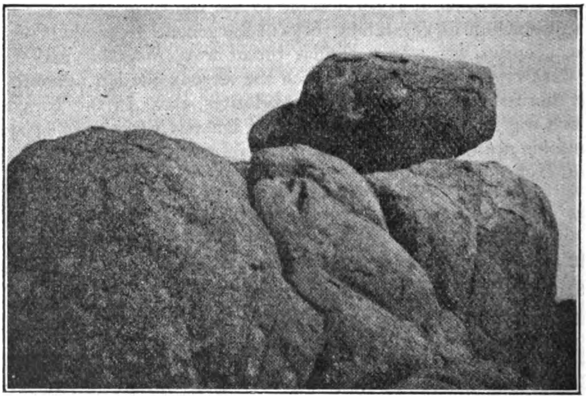


Fig. 241. Exfoliation of granite. Wichita Mountains, Okla.

and stable in composition. The carbonates are more soluble than most other common mineral substances.

Water may enter into combination with mineral matter, and the union is *hydration*. Thus when iron rusts (*oxidizes*), it is not merely oxygen which enters into combination with the iron, but water also. Iron rust is a hydrated oxide of iron (see limonite, p. 256).

Oxidation, carbonation, and hydration, involving respectively the addition of oxygen, carbon dioxide, and water, increase the volume of the mineral matter. The result is that the rock affected crumbles. Thus the iron rust formed on a knife blade crumbles off. So the iron rust formed when oxygen and water unite with the iron in the rock, causes the rock in which the change takes place to crumble, partly because of the expansion involved.

Again, some of the simple compounds, especially the carbonates, formed when the rock decays, are somewhat soluble and may be dissolved and taken away. This tends to make the rock less compact by taking away one of its ingredients.

Oxidation, carbonation, and hydration therefore not only

change the chemical nature of the rock, but they change its volume, allow some of its material to be carried off in solution, and in many cases cause it to fall to pieces. The result is decayed rock — or one variety of *rock waste*. It is to be observed that the rock waste which arises from decay is unlike the original rock in composition.

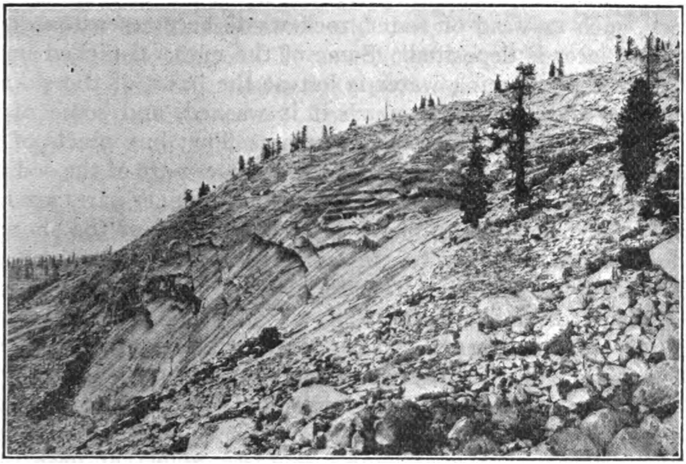


Fig. 242. Exfoliation on the slope of a granite mountain near Royal Arch Lake, Yosemite Quadrangle. (Turner, U. S. Geol. Surv.)

Some things have been added, and others taken away. In this respect, the waste arising from decay is unlike that arising from rock breaking.

The products of decay may remain where formed, or may be taken away. If they remain where formed for long periods of time, they may come to make a thick mantle of residual earth. Decayed rock is scores of feet in depth in many places, and hundreds of feet in some. Chemical decomposition is greatest in warm regions, and products of decay are least readily removed where there are forests. The products of decay are therefore likely to be deepest in warm, forested regions. They are very deep, for example, in some parts of Brazil.

### SEDIMENTATION AND SEDIMENTARY ROCKS

**Removal of decayed rock.** The breaking-up of igneous rock prepares the way for other processes. The loosened material may be blown away by the wind, washed away by running water, or

moved by any agency which shifts materials about on the surface of the earth. If the products of rock disintegration are coarse, they may become *gravel* after being rounded by streams or waves. If the material is finer, say of the size of small grains, it is *sand*; if still finer, it is *mud* when wet, and *dust* when dry.

**Deposition of sediment.** When carried by any transporting agency, such as wind or water, rock waste becomes *sediment*, and sooner or later is deposited. Some of the material picked up and transported by running water is left at the bases of the slopes of mountains and hills from which it is washed, and some of it is left on the flats through which streams flow; but much of it is carried to the sea and left there. The coarser part of the sediment carried to the sea is left near the shore, and the finer parts are taken farther out. Thus along many coasts the gravel of the shore-line grades out into sand, and this into mud as distance from the water's edge increases. The coarser materials are thus separated more or less perfectly from the finer.

When the disintegration of the parent rock results from decay, the rock-waste is unlike the parent rock in composition, because some of the original material has been dissolved and carried away in solution. Not only this, but the fine products of decay may differ from the coarser in composition. Thus the quartz grains of granite are generally large enough to be readily seen individually; and as the granite decays, this mineral, already a simple compound, undergoes little change, and the grains remain in the rock waste. By moving water, they are rounded into the sand grains with which we are familiar. On the other hand, the crystals of feldspar, which have a complex composition, decompose into very fine particles of *kaolin* (p. 257) or clay, unlike the feldspar in composition, and containing but a few of the elements of feldspar. Thus it happens that the coarser products of decay, such as quartz, are chemically unlike the finer, such as clay, and the two are partly separated when they are deposited. In this case, the composition of the rocks formed from the sediments may be very different from that of the rock from which the sediments were derived. On the other hand, when rock-waste resulting from the mechanical breaking of rock is deposited, the sediment has about the same composition as the rock from which it came. Sediment which contains feldspar derived from granitic rock is called *arkose*. Arkose represents incomplete decomposition of the parent rock.

**Cementation of sediment into solid rock.** After gravel, sand, mud, etc., are deposited in the sea or elsewhere, they may be cemented into solid rock by the deposition of mineral matter held in solution in water. This cement binds the pebbles, the grains, and the smaller particles together, much as lime binds sand in mortar. The cemented gravel makes *conglomerate*, or if the pieces of rock are angular, *breccia*; the cemented sand makes *sandstone*; and the cemented mud makes *shale*. These are common sorts of sedimentary rock. The cementation may take place while sedimentation is in progress, or at a later time. Conglomerate, sandstone, and shale, made up chiefly of particles derived directly from other rock, are *clastic* rocks. Limestone may be broken up, and its particles redeposited and cemented again into solid rock. Such limestone is clastic, and limestone made of broken shells, coral, etc., is in some sense clastic. In contrast with igneous rocks, clastic rocks are made up of particles of other rock, *particles which were once separate and distinct*, bound together by some sort of cement. The particles touch one another, but do not interlock like crystals of igneous rock.

When sand, mud, etc., are deposited in the sea, shells of sea animals may be imbedded in them. If the shells or their forms are preserved, they record the kinds of life that lived when the sediment was being laid down. If the sediments are deposited in lakes or on land, the shells or other relics of freshwater or land life may be buried in them. All distinct relics of past life are *fossils*.

**Non-clastic sediments.** Not all sedimentary rocks are clastic. It has already been noted that some of the compounds formed when rock decays are soluble. A part of the materials dissolved are carried in solution to the sea, where some of them are extracted by animals and made into shells or other hard parts. When the animals die, their shells and other secretions are left behind. If these are of calcium carbonate, they make *limestone* when cemented together. Much, if not most, limestone is composed of the secretions of organisms.

The shells, coral, etc., may or may not have been broken up before cementation. Limestone has many varieties, one of which is *chalk*. Magnesium may replace the calcium in various proportions, and if there is any considerable amount of magnesium, the rock is *dolomite*. The dolomization of some limestone (the conversion of $CaCO_3$ into $CaMg(CO_3)_2$) appears to have taken place long after the limestone was formed, while in other (perhaps in

most) cases it appears to have taken place while the material of the limestone was being deposited.

**Siliceous deposits.** In the decomposition of igneous rocks, a little of the silica, as well as of the bases, is dissolved and carried away in solution. Certain organisms extract this silica from the water for their tests, shells, etc., just as others extract calcium carbonate. Siliceous secretions may form siliceous rocks. *Diatom and radiolarian* oozes of the deep sea are examples. Familiar examples

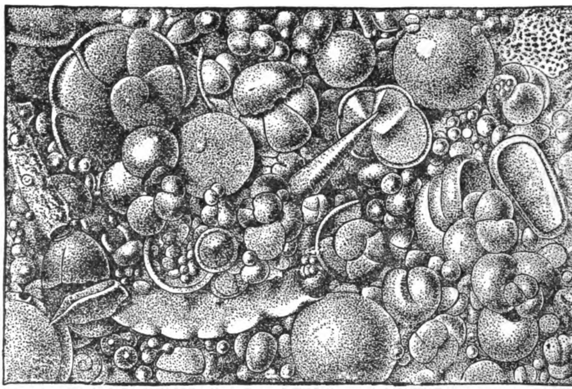


Fig. 243. Globigerina ooze, similar to chalk in composition. Magnified 20 times. (Murray and Renard.)

of indurated rock formed in this way are certain *flints* and *cherts* that occur in limestone, both as nodules and in distinct beds. Some of these are developed about fossil sponges.

**Precipitation from solution.** Some sedimentary rock is formed by direct precipitation from water which is saturated. Thus *limestone* might be formed by direct precipitation from water if it became saturated with $CaCO_3$, and some limestone has been formed in this way. *Rock-salt* has been deposited in thick beds at various times and places, as it is being deposited now about Salt Lake in Utah. The sodium of the salt (NaCl) doubtless came from decaying rock, for many igneous rocks contain a little sodium in some complex combination. In the decay of the rock, the sodium is taken out of its complex combination, and made into some soluble compound, and then taken to the sea or to a lake. Its union with chlorine makes common salt. *Gypsum* ($CaSO_4$) is another form of

rock deposited in a similar way. *Iron ore* occurs in large bodies, and some of them were formed by precipitation. Salt, gypsum, limestone, and iron ore are peculiar among rocks in that but one mineral enters into their composition when they are pure.

*Coal* is a sort of rock formed from accumulations of vegetable matter. Some other sedimentary rocks, as noted above, are formed organically, though they can hardly be said to be organic.

The principal classes of sedimentary rocks are given below:

| | |
|---|---|
| Mechanically formed<br>*Clastic* | Conglomeratic rocks,— gravel, conglomerate, breccia, etc.<br>Arenaceous rocks,— sand, sandstone, some arkose, etc.<br>Argillaceous rocks,— clay, shale, etc.<br>A few limestones. |
| Chemically formed<br>*Non-clastic* | Some carbonate rocks, e. g., travertine, siderite.<br>Chloride rocks,— especially rock-salt.<br>Sulphate rocks,— especially gypsum.<br>Some siliceous rocks,— some cherts, etc. |
| Organically formed<br>*Non-clastic* | Calcareous rocks,— most limestones.<br>Siliceous rocks,— siliceous oozes, sinter, etc.<br>Carbonaceous,— coal, etc. |

### *Distinctive Features of Sedimentary Rocks*

**Stratification.** Most sedimentary rocks are arranged in more or less distinct layers; that is, they are *stratified* (Fig. 2). Stratification consists primarily in the superposition of layers one on another. Layers of like constitution or compactness may be separated by films of different material which cause the partings. The bedded arrangement is due to various causes, but primarily to the varying agitation of the waters in which the sediments were laid down. Where depositing waters are agitated vigorously to the bottom, coarse sediment only is deposited. Where waters are quiet at the bottom, fine sediment is the rule. Since the agitation of waters is subject to frequent change, coarser sediment succeeds finer, and vice versa, in the same place. Hence arise *beds*, *layers*, and *laminæ*. The terms *layer* and *bed* generally are used as synonyms, while *laminæ* are thinner divisions of the same sort. The term *stratum* is sometimes applied to one layer, and sometimes to all the consecutive layers of the same sort of rock. For the latter meaning the term *formation* is often used.

The commoner sorts of bedded rock are limestones, shales, sandstones, and conglomerates. In many places the bedding of *limestone* is caused by films of clayey matter between the layers,

the films causing natural partings. Bedding arises also from variations in the physical condition of the calcareous sediment itself. Lamination is not, as a rule, conspicuous in pure limestone, though it may be in the shaly phases of this rock. *Shales* are normally laminated as well as bedded, and the lamination may be more notable than the thicker bedding. Bedding in shale may arise from the introduction of sandy laminæ, or by changes in the texture

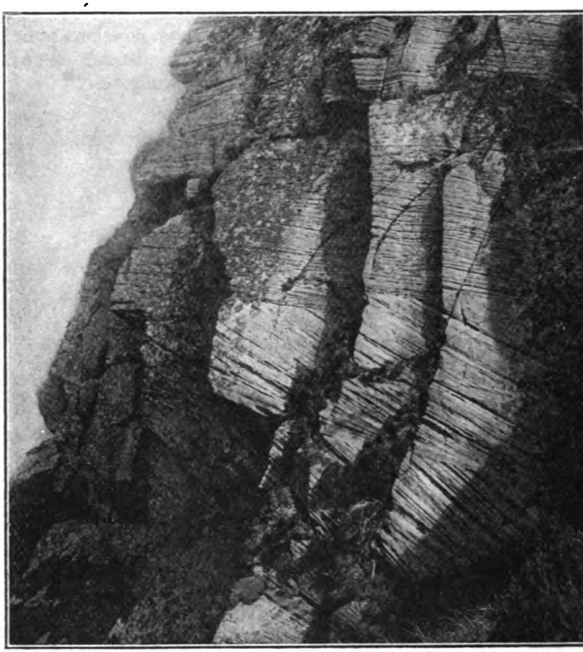


Fig. 244. Cross-bedded sandstone. Maol Donn, Arran. The layers are horizontal, some of the laminæ, diagonal. (H. M. Geol. Surv.)

of the mud, etc., of which the shale was made. Some *sandstones* are divided into beds by shaly or clayey partings, or by variations in the coarseness or coherence of the sand itself. Sandstones may be thick or thin-bedded, and their bedding passes insensibly into lamination.

Sand is deposited normally in relatively shallow water where it is subject to much shifting before it finds permanent lodgment.

In the shifting, bars or reefs are formed, most of which have a rather steep face in the direction in which the sand is shifted. The sand carried over the top of the bar finds lodgment on the sloping face beyond. The inclined laminæ thus formed constitute a kind of bedding, but its planes do not conform to the general horizontal attitude of the formation as a whole. The structure is called *cross-bedding*, or, more accurately, *cross-lamination* (Fig. 244). The same structure is developed on delta fronts, and generally in water shallow enough to be subject to frequent agitation at the bottom. Sandstone is cross-bedded more commonly than shale or limestone. The bedding of *conglomerate* is due chiefly to variations in coarseness. Laminæ or beds of sand occur between the layers of coarser material in many places. The beds of conglomerate are likely to be thick, and in conglomerate cross-bedding is common.

**Lateral gradation.** When the varying nature of the agitation of the sea at different depths and along the different parts of a coast is considered, it will be understood that deposits of one kind may grade into others horizontally. Thus a bed of conglomerate (gravel) may grade laterally into sandstone (sand), and this into shale (mud) or limestone. It is indeed more remarkable that sedimentary strata are as regular and persistent as they are, than that they grade into one another in some places.

**Position of strata.** At the time of deposition, beds of sediment conform in a general way to the slope of the bottom where they are laid down. Since the slope of the sea bottom near shore is very gentle, as a rule, beds of sediment are, in most cases, nearly horizontal when deposited. Their slope is rarely so much as 20°, and commonly less than 5°.

**Special markings.** The rhythmical action of waves gives rise to *ripple-marks* (Fig. 196), which are also made by streams, streamlike currents, and wind (Fig. 13). They are usually only a few inches from crest to crest, but in rare instances they attain much greater size. Under proper circumstances, ripple-marks are preserved indefinitely.

Some sediments are exposed between tides, or under other circumstances, for periods long enough to permit drying and cracking at the surface. On the return of the waters, the cracks may be filled and permanently preserved. (Figs. 200 and 201) Such records of sun cracks affect shales chiefly, but are seen occasionally in

limestones and fine-grained sandstones. During the exposure of the sediments, a shower may pass, and *raindrop impressions* (Fig. 245) be made which are subsequently filled by fine sediment and preserved.

**Unconformities.** Figs. 246, 247, and 248, show, in each case, one set of beds out of harmony with another set. This relation is one of

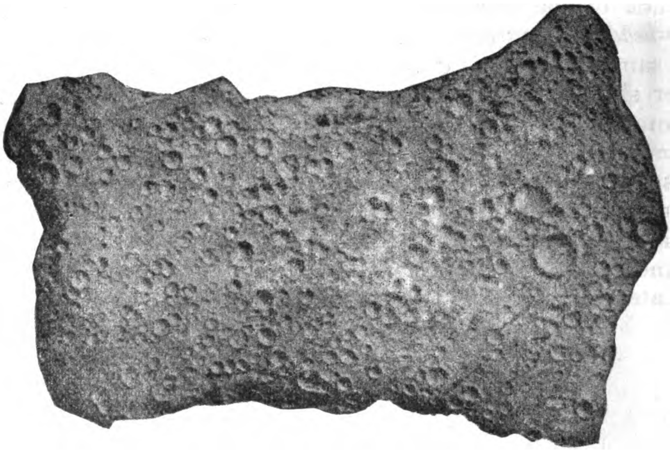


Fig. 245. Raindrop impressions. (Brigham.)

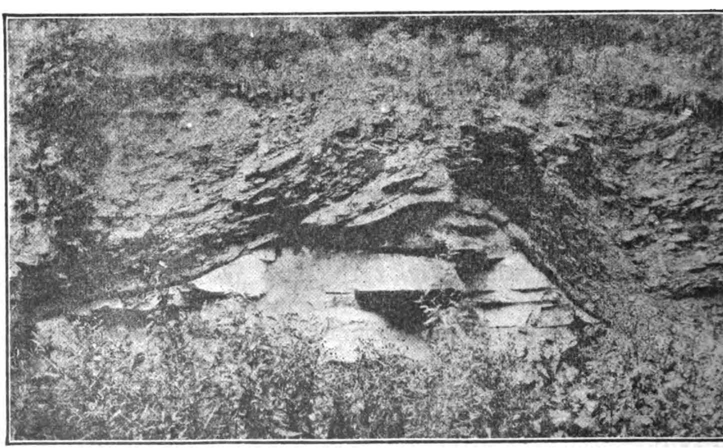


Fig. 246. Unconformity between the Devonian (the thick-bedded rock) below, and the Coal Measures (thin-bedded and broken) above. Iowa. (Udden.)

*unconformity*. Most unconformities are developed by the erosion, the deformation, or both, of the older and lower set of beds, before the deposition of the younger and upper set. The interval of time

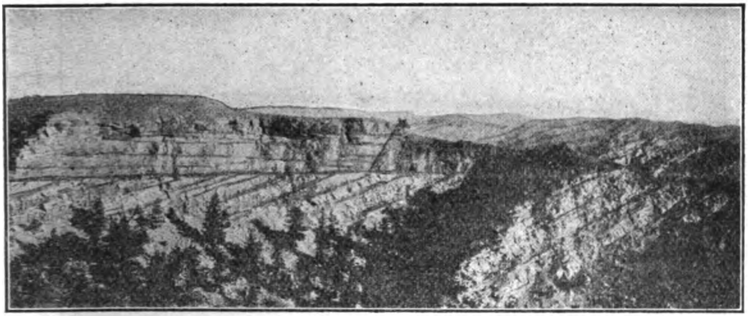


Fig. 247. Unconformity in Bighorn Basin, Wyoming. The lower (Laramie) beds dip notably to the left, and the upper horizontal (Wasatch) strata rest upon their cut-off edges. (Fisher, U. S. Geol. Surv.)

between the deposition of the unconformable sets of beds may be very long — when the unconformity is great, or short — when the unconformity may be slight. Unconformities are of great significance in the interpretation of geological history. Unconformities

Fig. 248. One phase of unconformity. The beds at the right were tilted to their present position before the deposition of the beds at the left.

exist between stratified rock and igneous rock, and between stratified rock and metamorphic rock, as well as between different series of bedded rocks.

### *Structural Features Arising from Disturbance*

**Inclination and folding of strata.** The original attitude of beds, whether formed by water or by lava-flows, commonly departs but little from horizontality. Locally, however, both kinds of deposits are made on considerable slopes.

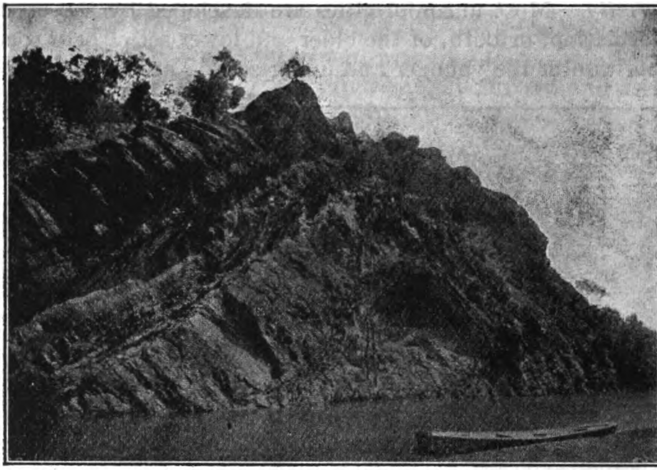


Fig. 249. Open anticlinal fold, near Hancock, Md. (U. S. Geol. Surv.)

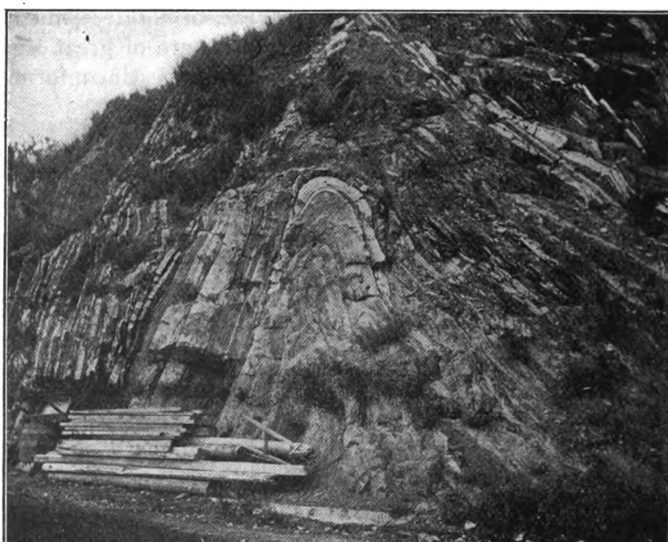


Fig. 250. Closed anticlinal fold, near Levis Station, Quebec. (U. S. Geol. Surv.)

Many sedimentary rocks and many lava flows have lost their original position through crustal movements, so that beds which were once horizontal now *dip*; that is, they depart from horizontality. The beds of a given region may all dip in one direction, or the dip may change from point to point. They may be folded, and the folds may be open (Fig. 249) or closed (Fig. 250). The beds of sedimentary rock may even be on edge (Fig. 251), having a dip of 90°. These diverse positions in which strata are found are the result of disturbance subsequent to their deposition.

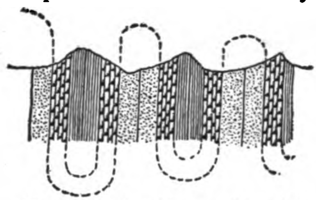


Fig. 251. Isocline. (Van Hise, U. S. Geol. Surv.)

Modifications of the original attitude result from earth movements, and the measurement of these modifications is an important part of field study. The position of beds is recorded in terms of *dip* and *strike*. The *dip* is the inclination of beds referred to a horizontal plane (Fig. 252) and is usually measured by a clinometer. In measuring the dip, the maximum angle of slope is always taken, and its direction as well as its amount is recorded. Thus dip 40°, S. 20° W., gives the full record of the position of the bed of rock under consideration. The *strike* is the direction of the horizontal edge of dipping beds, or more generally, the direction of a horizontal line along the outcropping edge of a dipping bed, as illustrated in Fig. 252. Since the strike is always at right angles to dip, strike need not be recorded if the direction of the dip is. Thus dip 40°, S. 20° W. is the same as dip 40°, strike N. 70° W.


Fig. 252. Diagram illustrating dip and strike.

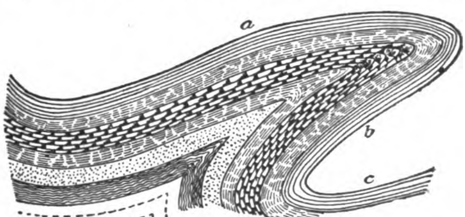



Fig. 253. Recumbent anticline. (Van Hise, U. S. Geol. Surv.)

When beds incline in a single direction, they form a *monocline*. When they are arched up as in a fold, they form an *anticline* (Figs. 249 and 250). The anticline may depart from its simple form, as

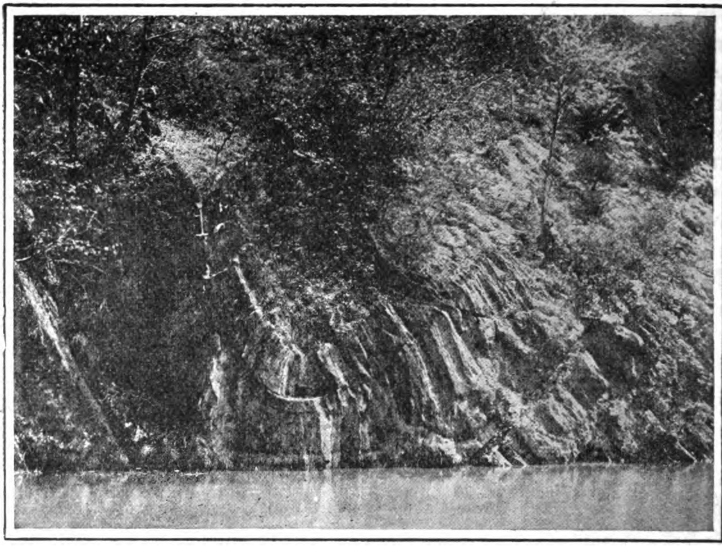


Fig. 254. Syncline, C. and O. canal, 3 miles west of Hancock, Md. Shale and sandstone, near base of the Silurian. (Walcott, U. S. Geol. Surv.)

shown in Fig. 253. The downfold corresponding to an anticline is a *syncline* (Fig 254.) When beds assume the position shown in Fig. 251, the folds are *isoclinal*. When considerable tracts are bent so as to form great arches or great troughs with many minor undula-

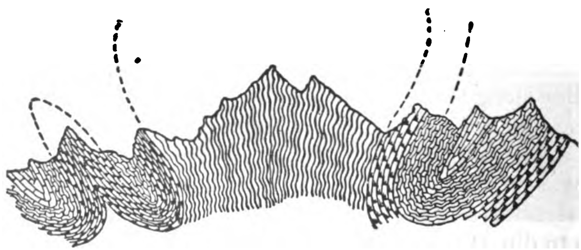


Fig. 255. Generalized fan fold of the central massif of the Alps. (Heim.)

tions on the flanks of the larger, they are called *geanticlines*, or *anticlinoria* (Figs. 219 and 255), and *geosynclines* or *synclinoria* (Fig. 256). Folding may be accompanied by the development of slaty cleavage (p. 293).

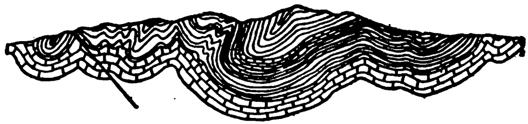
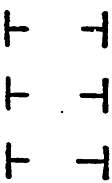


Fig. 256. Synclinorium, Mt. Greylock, Mass. (Dale, U. S. Geol. Surv.)

As found in the field, most folds are much eroded, and in many cases completely truncated (Fig. 255). The structure is then determined by a careful record of dips and strikes. On the field map, the record may be made as shown in Figs. 257 and 259, where the free ends of the lines with but one free end, point in the direction of dip, while the other lines represent the directions of strike. Applying this method, the structure shown in Fig. 257 represents a syncline, and that in Fig. 259 an anticline. In cross-section, the structure represented by Fig. 257 is shown in Fig. 258; that of Fig. 259, in Fig. 260.



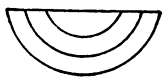
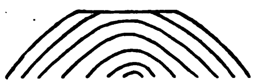


Fig. 258



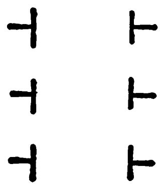


Fig. 257 Fig. 260 Fig. 259

Fig. 257. Map record of dip and strike, showing synclinal structure.

Fig. 258. Diagram showing the structure corresponding with Fig. 257, as seen in cross-section.

Fig. 259. Map record of dip and strike showing anticlinal structure.

Fig. 260. The structure of the area shown in Fig. 259, in cross-section.

Fig. 261 shows a doubly pitching anticline; that is, an anticline the axis of which dips down at either end. Fig. 262 shows a combination of synclines and anticlines, and Fig. 263 a cross-section along the line *ab* of Fig. 262. The outcrops of rock where the dip and strike can be determined may be few and far between, but when they are sufficiently near one

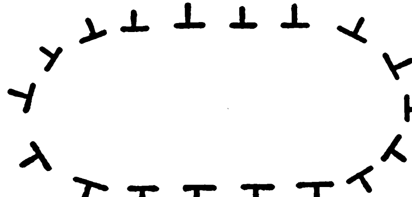


Fig. 261. Map record of dip and strike showing plunging (dipping down at ends) anticline.

another, the structure of the rock, as shown in Figs. 262 and 263, may be worked out, even though the surface is flat.

Much the larger portion of the earth's surface is occupied by beds that depart but little from their original horizontal attitude, but in many mountainous regions the beds have suffered bending, folding, crumpling, and crushing, in various degrees. Distortion is on the whole most considerable in the most ancient rocks. Distortion is assigned chiefly to lateral thrust arising from the shrinkage of the earth, as explained in Chapter VIII.

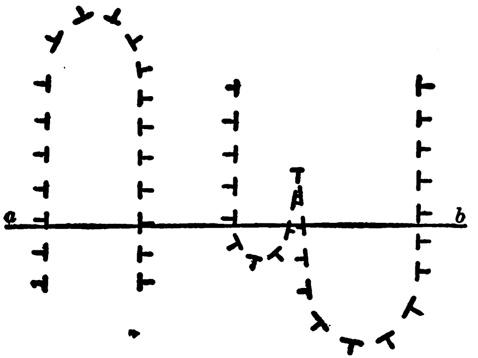



Fig. 262. Map record of dip and strike showing complex structure.

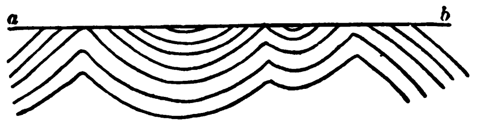



Fig. 263. Cross-section of Fig. 262, along the line *ab*.

Complicated structures may be very difficult of interpretation. Thus overturned folds reverse the order of the strata in the under limb of the fold (Fig. 253). After such folds have been greatly eroded, so that their outer form is lost and their relations have become obscure, the beds are likely to be interpreted as though they lay in natural order. Thus Fig. 264 might represent a simple monoclinal structure, or any one of the complex structures shown in Figs. 265, 266, or 267, so far as dip and strike show.

Fig. 264. Diagram representing either isoclinal or monoclinal structure.

**Joints.** The surface rocks of the earth are almost universally traversed by deep cracks called *joints* (Figs. 2 and 268). In most regions there are at least two systems of joints, the members of each system being roughly parallel, while those of the two systems, where there are two, are approximately at right angles. In regions of great disturbance, the number of sets of joints may be three, four, or even more. The joints of each set may be many yards apart, or in exceptional cases, inches, or even a fraction of one inch.

In horizontal rocks the joints approach verticality, but where the rocks have been deformed notably, the joint planes may have any position. In igneous and metamorphic rocks they may simu-

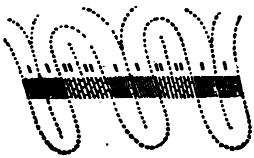


Fig. 265

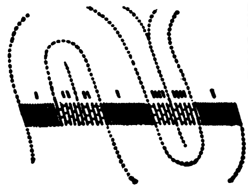


Fig. 266

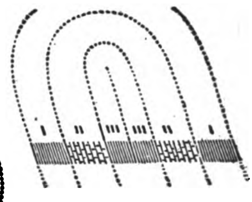


Fig. 267

Fig. 265. A possible interpretation of Fig. 264. (Dana.)
Fig. 266. A possible interpretation of Fig. 264. (Dana.)
Fig. 267. A possible interpretation of Fig. 264. (Dana.)

late bedding planes (Fig. 269). Joints do not ordinarily show themselves at the surface in regions where there is much mantle rock, but they are readily seen in the faces of cliffs, in quarries, and, in general, wherever rock is exposed. Though some of them extend to greater depths than rock has ever been penetrated, they are believed to be relatively superficial phenomena. They must be limited to the zone of fracture, and most of them are probably much more narrowly limited. Many joints end at the plane of contact of two

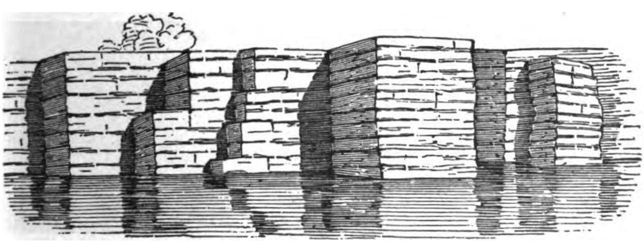


Fig. 268. Jointed rocks. Cayuga Lake, N Y. (Hall.)

sorts of rock. Thus a joint extending down through limestone may end where shale is reached. Joints may be offset at the contact of layers or formations, and a single joint may give place to many smaller ones. All these phenomena may be explained by the varying elasticity of various sorts of rock. Generally speaking, rigid rock is more readily jointed than that which is more yielding.

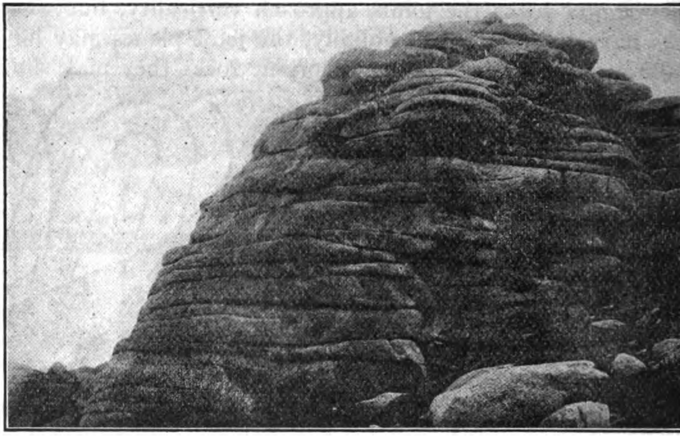


Fig. 269. Tabular joints in granite. Summit of Goatfell, Arran. (H. M. Geol. Surv.)

Fig. 270. A surface of sandstone marked by numerous joints, chiefly in two rectangular sets. Near Kinghorn, Fife. (H. M. Geol. Surv.)

Joints may remain closed, or may gape. They may be widened by solution, weathering, etc., and they may be filled by detritus from above, or by mineral matter deposited from solution (veins, p. 286). Many rich ore-veins are developed along joint-planes. (p. 45).

Joints have been referred to various causes, among which tension, torsion, earthquakes, and shearing are the most important. Most of them may probably be referred to the tension or compression connected with crustal movements.[1] In the formation of a simple fold, for example, tension-joints parallel with the fold will be developed if tension goes beyond the limit of elasticity of the rock involved. If the axis of a fold is not horizontal, that is, if it pitches, as it commonly does, a second set of tension-joints roughly perpendicular to the first may be developed. If the uplift is dome-shaped and sufficient to develop joints, they will radiate from the center. It is true that joints affect regions where the rocks have not been folded, and where they have been deformed but little, but deformation to a slight extent is well-nigh universal. Shrinkage is a cause of certain minor tension-jointing. The columnar structure of lavas and sun cracks are examples. These causes, however, are not believed to affect rock to great depths.

Exceptionally, open joints are filled by the intrusion of sedimentary material from beneath. Thus have arisen the remarkable *sandstone dikes*[2] of the West, especially of California. Some such dikes are several miles (nine at least) in length. The sand of these dikes was forced up from beneath either by earthquake movements or by hydrostatic pressure.

**Faults.**[3] The beds on one side of a joint-plane or fissure may be raised or sunk relative to those on the opposite side. Such a displacement is one type of a *fault* (Figs. 271 and 272). Fault-planes vary from verticality to horizontality. The angle by

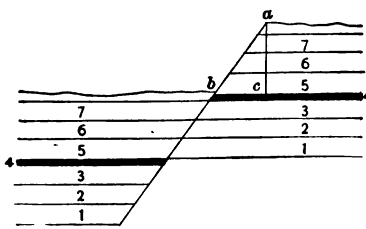



Fig. 271. A normal fault.

[1] Van Hise. Principles of North American Pre-Cambrian Geology; 16th Ann. Rept., U. S. Geol. Surv., Pt. I, pp. 668–672.

[2] Diller. Bull. Geol. Soc. Am., Vol. I, pp. 441–442. Ibid., Hay, Vol. III, pp. 50–55; and Newsom, ibid., Vol. XIV, pp. 227–268.

[3] Various articles in Economic Geology, Vols. I and II; Chamberlin, Fairchild, Jaggar, Ransome, Reid, Spurr, and Willis.

which the fault-plane departs from the vertical is the *hade* (*bac*, Fig. 271). The vertical displacement (*ac*) is the *throw*, and the horizontal displacement (*bc*) the *heave*. The *displacement* is the amount of movement along the fault-plane, *ab*. The cliff above the edge of the downthrow side is a *fault-scarp*. In many cases the scarp has been destroyed by erosion; but a few fault-scarps of mountainous heights are known, as along some of the basin ranges of Utah and Nevada. Most fault-scarps which persist are much modified by erosion.

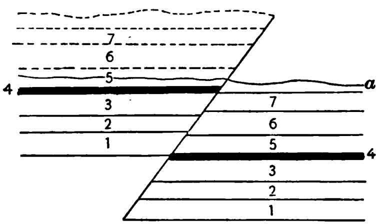



Fig. 272. A thrust-fault. The dotted lines at the left show the portion which has been removed by erosion. The present surface is shown by the line to the left of *a*.

Faults involving vertical displacement along joints are of two general classes, *normal* (or *gravity*) and *reversed* (or *thrust*). In the normal fault (Fig. 271) the overhanging side is the downthrow side, i. e., the downthrow is on the side towards which the fault-plane declines. Normal faults, as a rule, indicate an extension of strata, this being necessary to permit one of the dissevered blocks to settle. In the thrust fault (Fig. 272), the overhanging beds appear to have moved up the slope of the fault-plane, as though the displacement took

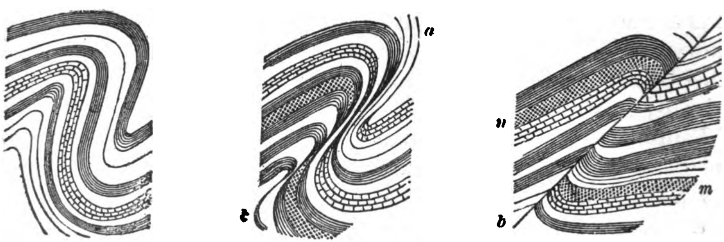



Fig. 273. Diagrams showing relations of faults and folds.

place under lateral pressure. This is clearly shown to be the case where an overfold passes into a thrust fault. Another type of thrust-fault is shown in Fig. 273.

In thrust-faults, the heave may be great. The eastern face of the Rocky Mountains near the boundary-line between the United States and Canada has been pushed over the strata of the bordering

plains to a distance of at least seven miles.[1] Overthrusts of comparable displacement have been detected in Scotland[2] and elsewhere.

Some faults branch, and in some cases the faulting is along a series of parallel planes near one another, instead of being along a single plane. Such a fault is *distributive* (Fig. 274). Faults are found to die out when traced horizontally, in some cases by passing into monoclinal folds (Fig. 275), and in some cases without connection with folding. In depth they probably die out in various ways (Fig. 276). A fault of thousands, or even hundreds of feet is probably the sum of numerous slight slippings distributed through long intervals of time. The faulting along one plane may be the cause of many earthquakes.

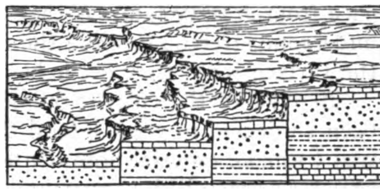


Fig. 274. A branching fault. (Powell, U. S. Geol. Surv.)

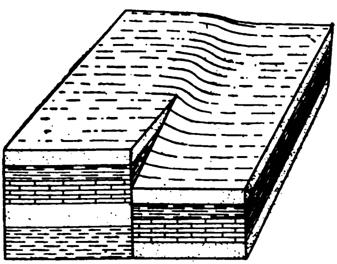


Fig. 275. Diagram of a fault passing into a monoclinal fold.

Fig. 276. The fault above grades into a fold below. Thickening and thinning of layers next the fault-plane is evident. Based on experiments of Willis. (13th Ann. Rept., U. S. Geol. Surv.)

The rock on either side of a fault-plane may be smoothed as the result of the friction of movement. Such smoothed surfaces are *slickensides*.

**The significance of gravity and thrust faults.**[3] Faults afford an indication of the conditions of stress and tension to which a region has been subjected, but some caution must be exercised in

[1] Willis, Bull. Geol. Soc. of Am., Vol. XIII, pp. 331–336, and McConnell, Canada Geol. and Nat. Hist. Surv., 1886, Pt. II.

[2] Geikie, Text-book of Geology.

[3] Van Hise, Sixteenth Ann. Rept., U. S. Geol. Surv., Pt. I, pp. 672–678.

their interpretation. Most gravity faults indicate an extension of the surface sufficient to permit the fault-blocks to settle down unequally. Thrust faults, as a rule, signify a compression of the surface which required the blocks to overlap one another. In other words, normal faulting usually implies tensional stress, and reversed faulting compressional stress. Exceptional cases aside, the inference from gravity faults is that the regions where they occur have undergone stretching, while the inference from thrust-faults is that the surface when they occur has undergone compression.

In view of the current opinion that the crust of the earth has been subjected to great lateral thrust as a result of shrinking, it is well to make especial note of the fact that the faults which imply *stretching* are called *normal* because they are the more numerous; and that the faults which imply thrust are the less common. The testimony of normal faults in favor of tension is supported by the prevalence of gaping crevices, and veins. All these phenomena seem to testify to a *stretched* condition of the larger part of the surface of the continents.

Faulting may bring about numerous complications in the outcrops of rock formations. These are difficult of detection in some cases, especially after erosion has destroyed the fault-scarps.[1]

**Faults of horizontal displacement.** Horizontal displacement may take place along a joint-plane, with no vertical displacement. This also is faulting. Horizontal displacement accompanies vertical displacement, in many cases, and the former is as much a part of the faulting as the latter. The tendency of recent study, whether based on theory or on field observation, is to emphasize the importance of the horizontal movement in faulting. In many mines, for example, where the walls of shafts and tunnels afford excellent opportunity for observation, horizontal movement is more in evidence than vertical.

There are various displacements of rock bodies not mentioned above which are akin to faulting, if not to be regarded as such. Thus when strata are folded there is some slipping of layer on layer. In places there is displacement of layer on layer, even when the beds are not folded. Such a case with a well developed "*slickenside*" contact is known in Ohio, between beds which are nearly horizontal. The recognition of such movements as faults opens a wide door. The great variety of displacements along joints or other partings in

[1] See authors' Geologic Processes, pp. 522–524.

the rock, shows the difficulty of defining faults sharply. Many movements of displacement, which can hardly be separated from faults logically, are not usually called faults.

*Map work.* The sections of the Structure Section Sheets of the folios of the U. S. Geol. Surv. furnish abundant illustrations of a variety of structural features, such as folding and faulting, and the relations of sedimentary, metamorphic, and igneous rocks. The sections of various Bulletins, Professional Papers, etc., of the same Survey afford other illustrations. See also Exercise XVII in Interpretation of Topographic Maps.

### INTERNAL CHANGES IN IGNEOUS AND SEDIMENTARY ROCKS; METAMORPHISM

We have seen already that igneous rocks undergo physical and chemical changes, whereby they are disintegrated, giving rise to what has been called *rock waste:* Similarly, sedimentary rocks may be decomposed and converted into waste. The waste from one generation of rock is the raw material for rock of a new generation. It is "rock waste" in somewhat the same sense that lumber is forest waste.

Properly speaking, all changes which rocks undergo after being formed are metamorphic changes. According to this view, decayed rock is a phase of metamorphic rock; but it has been customary in the past to limit the term "metamorphic" to rocks which are made more compact, more complex in constitution, or more crystalline. Both sedimentary and igneous rocks may be metamorphosed.

**Induration of sediments.** The first step in the alteration of sediments is their induration, through the aid of cement, pressure, etc. Sandstone and shale are not commonly called metamorphic rocks, but they are metamorphosed sand and mud, respectively. The cementing material of sediment, as already noted, is mineral matter deposited from solution in water. Thus mineral matter dissolved at and near the surface may be carried down by descending water, and deposited between the grains of sediment, binding them together. The cementation may be slight, or it may go so far that all the spaces between the grains of sediment are filled. When the spaces between sand grains are filled with silica, the rock becomes *quartzite.* Between loose sand at the one extreme, and quartzite at the other, there are all gradations. Quartzite is classed as metamorphic rock, but it is formed by a continuation of the process which converts sand into sandstone. Important changes in rock are

brought about by the solution and re-deposition of mineral matter by the water in the rocks. This process may be called *aqueous metamorphism,* because of the important part played by water. Since water is present in almost all rocks down to considerable depths, the changes which it produces are nearly universal down to the depths to which it penetrates.

**Cavity filling.** Cavities in rocks larger than the spaces between grains also receive deposits, if the waters entering them carry mineral matter in solution. Thus joints or cracks may be filled with mineral matter, making *veins* (Fig. 277). The *agates* developed in some cavities afford another illustration of cavity filling. Here the successive layers are commonly of quartz, differing from one another in color and texture. *Geodes* are cavities partly filled with crystals (Fig. 278), mostly of quartz or calcite.

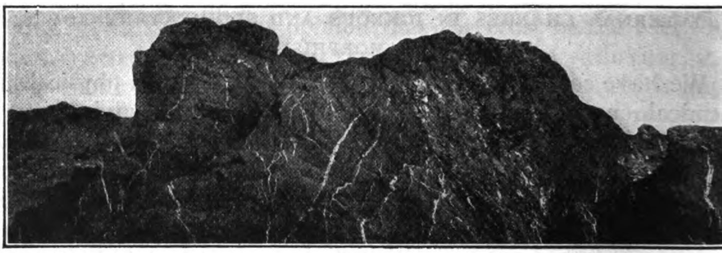


Fig. 277. Veins of calcite in volcanic tuff. Shore west of Kincraig Point, Elie, Fife. (H. M. Geol. Surv.)

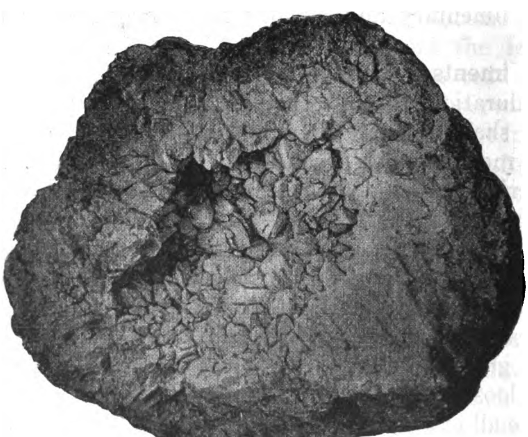


Fig. 278. Geode. (Bassler, U. S. Geol. Surv.)

**Replacements.** In both sedimentary and igneous rocks there are replacements. Thus through the dissolving and depositing action of water the

calcium carbonate of corals, shells, etc., may be replaced by silica. The substitution may take place so that even the minutest details of structure are preserved. Woody matter is, under proper conditions, replaced by silica, forming *petrified* wood.

The material of one crystál may be replaced by different material, as the molecules of calcite by zinc carbonate. This gives a *pseudomorph* of zinc carbonate after calcite, the zinc carbonate taking the form of calcite, instead of the form which it would take if crystallizing under other circumstances. This sort of change may affect the crystals in any sort of rock.

**Concretions.** Another phase of the internal reconstruction of sedimentary rocks is the assembling of matter of the same kind. For instance, silica that was deposited in the form of siliceous shells

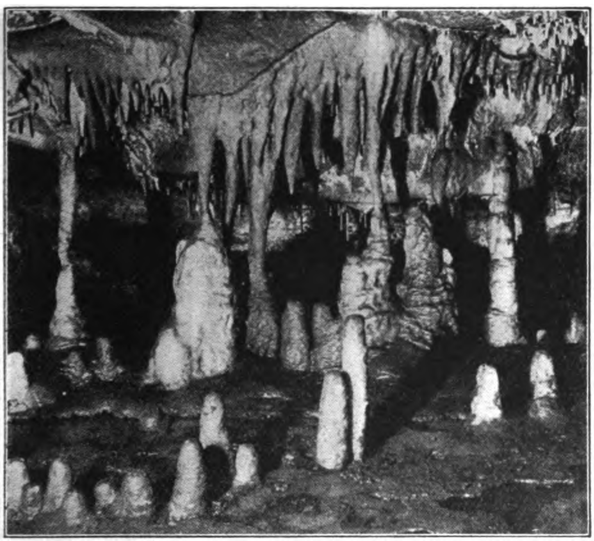


Fig. 279. Deposits of calcite (travertine, stalactites, and stalagmites) in Wyandotte Cave, Ind. (Hains.)

and spicules of plants and animals, and disseminated through the sediments as they were deposited, may be aggregated later into nodules or *concretions* of chert or flint (Fig. 280). Similarly, concretions of calcium carbonate or iron carbonate grow in silts or muds. In many other cases, too, kind comes to kind.

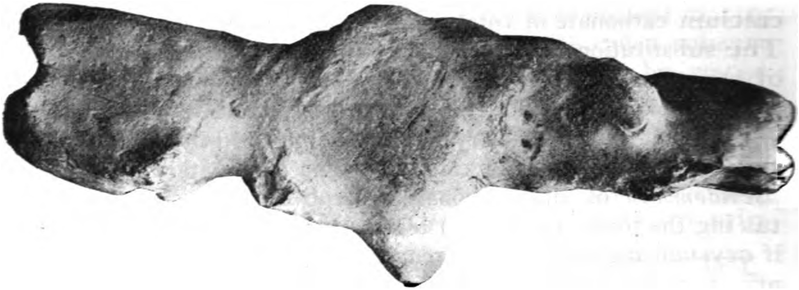


Fig. 280. Nodule of chert, about half natural size. (Photo. by Church.)

In general, concretions are made by the deposition of mineral matter which was in solution, about a nucleus. The nucleus

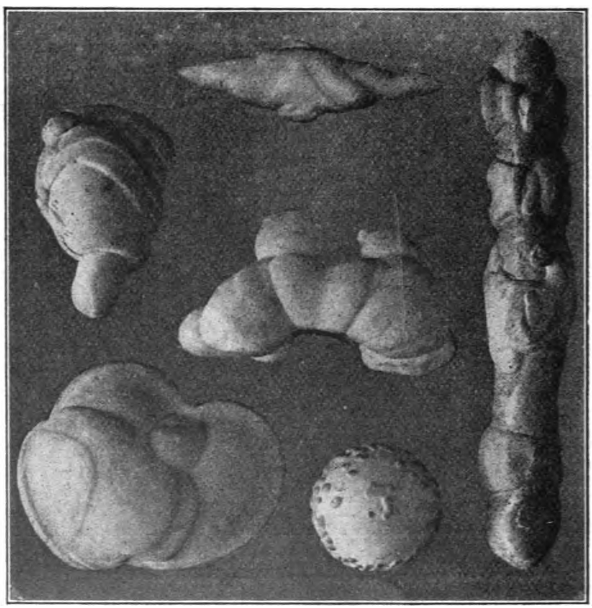


Fig. 281. Irregular calcareous concretions. Ryegate, Vt. (Photo. by Church.)

may be a leaf, a shell, or some bit of organic or inorganic matter. The material of the concretion probably comes, in most cases, from the immediately surrounding rock. Concretions are generally

of matter unlike that of the rock in which they form. Thus concretions of calcium carbonate (Fig. 281) are common in clay, concretions of chert (silica) (Fig. 289) in limestone, and concretions of iron oxide in sandstone.

Many concretions develop after the enclosing sediment was deposited. This is shown, in some cases, by the fact that bedding planes run through the concretions. Concretions also form in sediments during their deposition, and exceptionally, rock is made up chiefly of them. The chemical precipitates from the concentrated waters of certain enclosed lakes may take the form of minute spherules. From a fancied resemblance of these concretions to the roe of fish, the resulting rock was called *oölite* (Fig. 282). Oölite is now forming about some coral reefs, presumably from the precipitation of lime carbonate temporarily in solution. Some considerable beds of limestone are oölitic. The calcium carbonate of such rock may be replaced by silica, leaving the oölitic structure in siliceous rock. Some beds of iron ore are concretionary. Thus there are widespread beds of "flax-seed" iron ore made up of concretions of iron oxide which, individually, resemble the seed which has given the ore its name. Some concretions develop cracks within themselves, and the cracks may be filled with mineral matter differing in composition or color from that of the original concretion (Fig. 283). Such concretions are called *septaria*.

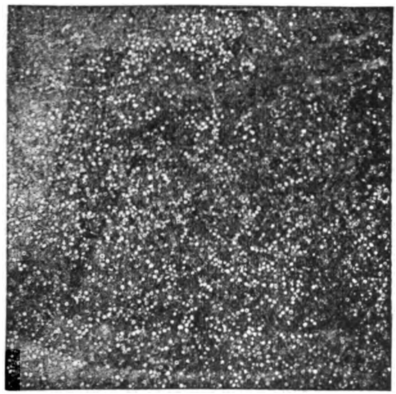


Fig. 282. Oölitic texture. About natural size. (Photo. by Church.)

In size, concretions vary from microscopic dimensions to huge masses, 10 or more feet in diameter. The variations in shape are also great, conditions of growth having much to do with the form. A concretion which starts as a sphere may find growth easier in one plane than another, when it becomes discoid. Two or more concretions may grow together, giving rise to complicated forms.

None of the changes thus far mentioned (p. 285 *et seq*) consti-

tute metamorphism, in the generally accepted meaning of the term, but all are metamorphic changes, if that term be given its largest meaning.

**Surface vs. deep-seated changes.** Near the surface, the action of water commonly tends to the decomposition of rock; but below a few hundred, or at most a few thousand feet, its general effect is

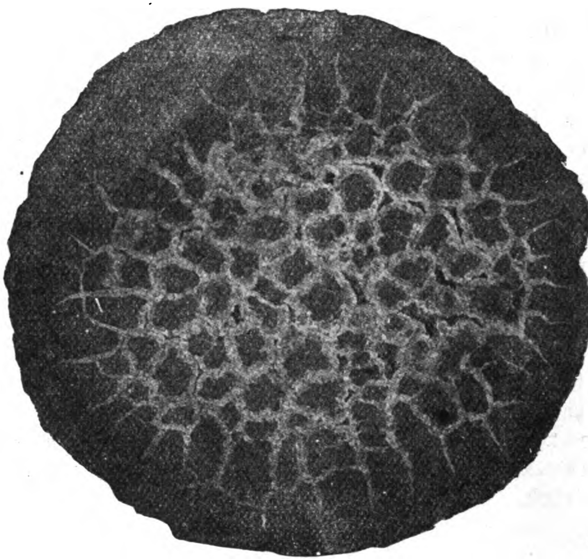


Fig. 283. Section of a septarian nodule (clay ironstone). About 3/8 natural size. (Geikie.)

to solidify the rock, for at these depths deposition exceeds solution, and oxidation, carbonation, etc., go on much more slowly than near the surface, or not at all. Oxidized and hydrated sediments may be buried to great depths, and under the pressure and perhaps the high temperature of these depths, deoxidation and dehydration may take place, with resulting diminution of volume. These changes at considerable depth are one phase of metamorphism, even according to the older use of the term.

**Incipient crystallization.** A common metamorphic change in sedimentary rock is incipient crystallization. Some limestones and dolomites are made up largely of small crystals, though the mass was originally a calcareous mud or ooze. New crystals also are

developed in shales and other sedimentary rocks out of materials already present, or with such additions as ground-water may make. Such changes take place even under ordinary conditions of heat and pressure, through the help of ground-water.

**Change in composition.** Besides simple deposition in pores and cracks, mineral matter in solution may enter into combination with other mineral matter, giving rise to new and in some cases to more complex and more compact mineral substances. The changes effected in this way go on slowly, but in the long course of time, they may go so far that none of the original rock material remains in its original condition — all having entered into new combinations. *Soapstone* or *steatite*, *serpentine*, *chloritic* and *talcose rocks*, all of which occur in large bodies, were developed primarily through the chemical rearrangement of the mineral matter of some older rock, with the addition of some mineral matter brought in by ground-water, and with the subtraction of some soluble matter. Their metamorphism is largely chemical.

**Other conditions favoring metamorphism.** Besides water, heat and pressure favor the metamorphism of rocks. Their action gives rise to three general cases, but these three blend indefinitely: (1) *great heat* without exceptional pressure, (2) *exceptional pressure* without great heat, and (3) *great heat and great pressure* acting together. Exceptional heat arises especially from the intrusion of lavas, and from pressure. Exceptional pressure arises chiefly from the weight of overlying rocks, and from lateral thrust due to shrinkage of the earth. Thrust generates heat as well as pressure. The water in the rocks greatly facilitates the chemical and mineralogical changes favored by heat and pressure.

**Metamorphism by heat.** When lava is poured out on the surface, it bakes the mantle-rock which it overflows. The extent of the baking depends on the mass and temperature of the lava. The nature of the effect is much the same as in the baking of brick. It consists in the *dehydration* of the *material*, its *induration* by welding due to partial fusion, and the *development of new compounds*. The time involved is short, the pressure slight, and the water action limited. If the heat were great enough, the loose material over which lava flows would be fused; but complete fusion does not usually take place when lava spreads out on the surface.

Intrusions of lava (p. 228) heat the surface above as well as that below. The heat of the lava can escape only through the neigh-

boring rock, and the changes effected by a given mass of lava are more considerable. Furthermore, the time during which the adjacent rock is hot, and therefore the time during which thermal waters are operative, is usually longer than in the case of extruded lavas, and the chemical and crystalline changes are greater. The changes are greater the greater the mass of the lava and the higher its temperature.

In limestones and sandstones the changes are simple, and in shales more complex. In pure *limestones* and *dolomites* little chemical change takes place, but the molecules are rearranged into larger crystals, making *marble.* The coarseness of the crystals is a rough sort of measure of the length of time during which the heat acts, and of its intensity; but much depends on the freedom of the attendant water circulation. If impurities, as silica, alumina, iron, etc., were present in the limestone, various silicate minerals may be formed in the marble. In pure quartzose *sandstones*, the effect is to bring about more complete cementation, converting the sandstone into *quartzite* (p. 285). Here, as in marbles, impurities form adventitious crystals. In *shales*, the material to be acted upon is more complex, for, while the main mass is composed of hydrous aluminum silicate, there is usually much free quartz, and in many cases some potash, soda, iron, compounds of calcium, magnesium, etc., for many muds from which shales arise contain not only the fully decomposed matter of the original crystalline rocks, but some fine matter worn from them by wind and water without decomposition. When this mixed matter is acted upon by high heat and moisture, it tends to return to its original crystalline state, so far as its changed composition permits. The result is the development of complex silicates, similar to those of igneous rocks, such as feldspar, mica, hornblende, etc. *Mica schists* are common products of the metamorphism of shales by contact with bodies of lava. Mica schists also are formed in other ways, and other schists, dependent on the composition of the shales, are formed about intrusions of igneous rock. In all such cases pressure probably attends the heat, and is a factor in the development of the schists. When the change induced by the heat is less considerable, the shale is baked, with incipient re-crystallization, and may take the form of *argillite*, a compact, massive sort of shale.

Beds of hydrous iron oxide (*limonite*) or of iron carbonate (*siderite*) may be converted by heat into hematite or magnetite (p. 255).

Beds of peat, lignite, and bituminous coal are converted into anthracite by the driving off of the volatile hydrocarbons. If the process goes to the extreme, graphite is the result.

**Metamorphism by pressure.** When rocks made up of clastic particles are compressed in one direction, and are relatively free to

Fig. 284. Figure showing the elongation of pebbles under pressure. Carboniferous formation, Newport, R. I. (Walcott, U. S. Geol. Surv.)

expand in others, the particles which are already elongated tend to turn so that their longer axes are at right angles to the direction of pressure, and all particles, whether elongate or not, are more or less flattened at right angles to the direction of stress. This is readily seen where the particles are large (Fig. 284). As a result of the turning (or *orientation*) and flattening of their particles, rocks so affected split more readily between the elongate and flattened particles than across them. In other words, the rocks *cleave* along planes normal to the direction of compression. The structure thus induced is known as slaty structure (Fig. 285), and is illustrated by roofing-slate, which was originally a mud, later a shale, and finally assumed the slaty condition under strong compression. In some cases the original bedding may still be seen running across the cleavage planes

Fig. 285. Pre-Cambrian fossiliferous slate. Deep Creek Canyon, 16 miles southeast of Townsend, Mont. (Walcott, U. S. Geol. Surv.)

developed by pressure (Fig. 286). As the original mud beds were horizontal or nearly so, and as thrust is most commonly horizontal or nearly so, the induced cleavage commonly crosses the bedding planes at a high angle. If the beds are tilted or bent before the development of the slaty cleavage, the angle between the bedding planes and the slaty cleavage may be small.

Limestones, sandstones, and conglomerates are not so easily compressed as mudstones, and they commonly take on only an imperfect cleavage normal to the direction of pressure.

**Foliation, schistosity.** Extreme pressure in a given direction is capable of breaking down and deforming the most resistant rock. This must necessarily be attended with the evolution of heat, and thermal effects are combined with pressure effects. The first effect

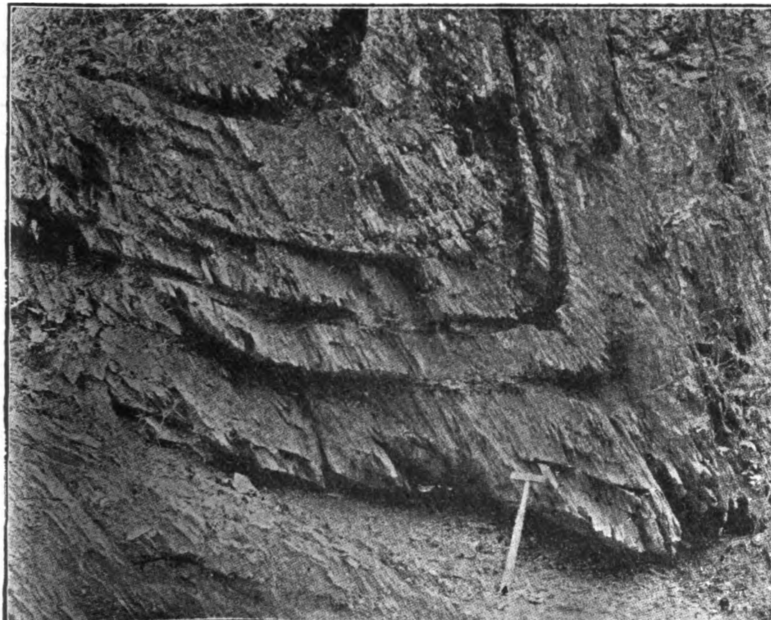


Fig. 286. Slaty structure and its relation to bedding planes. Two miles south of Walland, Tenn. (Keith, U. S. Geol. Surv.)

of the compression of such a rock as granite may be to crush it. It then becomes granular or fragmental, and is really a peculiar species of clastic rock (*autoclastic*). By further compression, the fragmented material may be pressed into layers or leaves, much as in the development of slaty cleavage; but as a result of the nature of the material, the cleavage is less perfect. These changes may be attended by more or less shearing of the material upon itself. The result is a *foliated* or *schistose structure* (Fig. 4), the most distinctive feature of highly metamorphic rock. A foliated structure may be developed even in the most massive rocks. Thus granite may be transformed into *gneiss* — which is like a granite in composition, but has a foliated structure, and basalt may be converted into *schist*, a common term for foliated crystalline rocks.

The kind of schist produced by metamorphism depends on the constitution of the rock metamorphosed. Basic rocks give rise to basic schists, and acidic rocks to acidic schists. It is obvious that

ordinary shales cannot become basic schists, because in the production of the muds from which shales are made, the bases were mostly removed; but shales which are highly calcareous and magnesian may be changed basic schists (*say hornblende schists*) by metamorphism. Schists are commonly named for the abundant cleav-

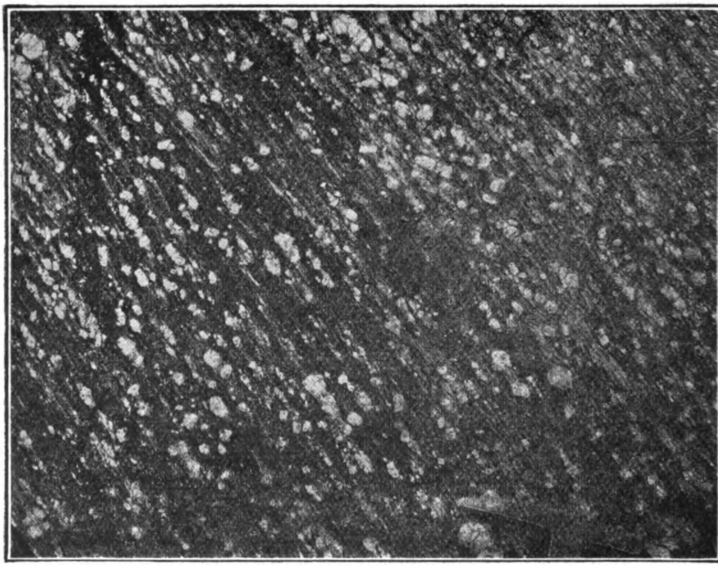


Fig. 287. Porphyry rendered schistose by pressure. Near Green Park, Caldwell Co., N. C. (Keith, U. S. Geol. Surv.)

able mineral constituent, as *mica schist* (chiefly of quartz and mica), *talc schist*, *chlorite schist*, etc.

The crystallizing processes of metamorphism are fundamentally similar to the processes by which rocks crystallize from lavas; but in metamorphism, the work is done chiefly by the aid of an aqueous solution, while in the solidification of lavas the crystallization is from a mutual solution of the constituents in one another, where water was but an incident.

Metamorphic rocks are of course subject to deformation and faulting, the same as sedimentary and igneous rocks. They are also subject to alteration through decay, or through the reorganization of their materials into new forms.

## VARIOUS CLASSIFICATIONS AND NOMENCLATURES

From the foregoing sketch of the processes of rock-making it will be understood that the varieties of rocks are many, and that they may be defined, named, and classified on many different bases; for example:

(1) If *the mode of origin* is chiefly in mind, rocks may be classed as *igneous* (lavas, tuffs, etc.); *metamorphic* (schists, gneisses, anthracite, etc.); and *sedimentary*. The last includes (*a*) *aqueous* (water-laid sediments, travertine, etc.); (*b*) *eolian* (wind-blown sand and dust); (*c*) *glacial* (deposits by glaciers); (*d*) *organic* (peat, coal, etc., and indirectly, limestone, infusorial earth, etc.).

(2) On the basis of *textural character*, rocks are designated vesicular (pumice, scoria, etc.); glassy (obsidian); porphyritic (p. 248); granitic or phaneritic (pp. 248 and 262); compact, porous, earthy, arenaceous (sandy), schistose, etc.

(3) If *chemical composition* is to be emphasized, they may be classed as siliceous, calcareous, carbonaceous, ferruginous, etc.; or, in case of igneous rocks, as acidic, basic, or neutral.

(4) If *crystallinity* is made the basis, igneous rocks are designated phanerites (crystals distinct), aphanites (crystals very small), porphyries, glasses, etc.

(5) On the basis of *mineral composition*, rocks are quartzose, micaceous, chloritic, pyritiferous, garnetiferous, etc.

(6) Regarded as *mineral aggregates*, some rocks are simple and some complex. If simple, they are named from the dominant minerals, as dolomite, hornblendite, etc.; if complex, they take special names, as syenite, gabbro (pp. 260, 262), etc.

(7) On the basis of *structure of the mass*, rocks are classed as massive, stratified, shaly, laminated, slaty, foliated, etc.

(8) When *physical state* and *genesis* are considered, they are clastic, fragmental, or detrital, (conglomeratic, brecciated p. 263, arenaceous, argillaceous (clayey), etc.); or pyroclastic (tufaceous, agglomeratic, p. 263), etc.

As one of these characteristics is most important in a given rock or in a given study, and another in another, no one classification is satisfactory in all cases.

# PART II

# HISTORICAL GEOLOGY

## CHAPTER XI

### THE ORIGIN OF THE EARTH

The bedded rocks of the earth's shell reveal its history far back into the past with great fidelity; but the record of the earlier ages is indistinct, and if we attempt to go back to the earth's beginning, the indistinctness merges into obscurity. The rocks below the well-bedded strata are so broken and altered, and so cut up by intrusions, that their history is read with great difficulty. Still lower lies the inaccessible interior of the earth whose nature is more a matter of inference than knowledge.

Some suggestions as to the origin of the earth are found in its relations to the other bodies of the solar system, and certain features of this system give pointed hints concerning its early history. The interpretation of these outside relations of the earth and of the secrets of its hidden interior is yet far from clear, and our only recourse is to hypotheses; but it is important that we study these hypotheses, and note the ways in which they enter into interpretations of the earth's phenomena, for not a few of the leading doctrines of geology hang on some hypothesis of the earth's beginning, and have no greater strength than the hypothesis on which they depend.

#### HYPOTHESES

It is the nearly unanimous conviction of astronomers that the solar system was evolved in some way from a nebula of *some form.* Until recently, astronomers so generally accepted the view of Laplace that it came to be known as "The Nebular Hypothesis"; but the advance of knowledge makes it necessary to consider other hypotheses which postulate that the solar system arose from a nebula whose constitution and mode of evolution differed from that

assumed by Laplace. The leading hypotheses of the earth's origin fall into three groups:

1. *The gaseous hypotheses*, in which the parent nebula is assumed to have been formed of gas collected into a spheroid by gravity, and to have been evolved into the present solar system by loss of heat, and the separation of the outer parts into planets. The type of the class is the Laplacian hypothesis.

2. *The meteoritic hypotheses*, in which the parent nebula is assumed to have been a swarm of meteorites, the members of which moved in diverse directions. Frequent collisions gave rise to heat, light, and vaporization. The swarm of meteorites is thought to have behaved essentially as a coarse gas, and the evolution of the system to have been dynamically like the preceding.

3. *The planetesimal hypothesis*, in which the original constituents of the nebula are assumed to have been small bodies, molecules or aggregates, moving in orbits about a common center and forming a disk-like system. The evolution consisted in the gathering of these small bodies (*planetesimals*) into planets and satellites. Dynamically, this hypothesis differs more from the other two than they do from each other.

1. **The Laplacian hypothesis.** During the last century the Laplacian hypothesis was generally accepted, and geological theories as to the early states of the earth, and as to many later events in its history, were built upon it. The hypothesis is so well known that a few sentences will recall its essential features. It holds that the sun, the planets, and the satellites were once parts of a glowing, rotating, spheroidal, gaseous nebula, which was expanded enough to occupy the whole space of the solar system. The nebula was assumed to have cooled by radiation of heat, and in cooling to have shrunk. The shrinkage accelerated the rate of rotation, and this increased the equatorial bulge which rotation developed. The progressive increase of cooling, rotation, and bulging finally led to the separation of an equatorial ring. As this ring cooled and contracted, it was disrupted and its substance gathered into a planet whose orbit lay in the plane the ring had occupied. A series of rings, separated in this way, gave rise to the several planets in turn, while the central mass formed the sun. The orbit of any planet bounds approximately the space assigned to the nebula at the birth of that planet. At the time of origin, the several planets were thought to be hot, gaseous, and rotating. Cooling and shrinkage

increased the rate of their rotation, and this caused equatorial bulging, till some of them, following the example of their parent body, shed rings which became satellites.

In support of this theory many harmonies in the motions of the members of the solar system were cited, and in the early days of the hypothesis, existing nebulæ were thought to give it support, for among them, *as then known*, there seemed to be nebulous aggregations in various stages of development, from diffuse nebulous masses to forms almost as concentrated as suns; but the best photographs now taken fail to show that any follow the lines of this hypothesis. Grave difficulties arise from the dynamics of the theory, but without some knowledge of celestial mechanics, it is not possible to appreciate the full force of the arguments against it. Some of them may be stated briefly.

1. In the evolution of a gaseous nebula, it is highly improbable that rings would be formed, for the molecules of gas would separate from the parent nebula one by one.

2. Even if rings were formed, there are grave difficulties in their development into spheroids as set forth by this hypothesis.

3. In the intensely hot condition of the assumed ring which was to form the earth and moon, its gravity could hardly have held its gases together. Even now the earth does not appear to hold permanently very light gases, though it holds the heavier ones.

4. It is probable that the material of a ring, such as the supposed earth-moon ring, would have cooled to solid particles long before it could collect into a spheroid. In this case no secondary ring to form a moon would be developed.

5. The inner satellite of Mars (*Phobos*) revolves about that planet three times while the planet rotates once. According to theory, these motions must have corresponded at the time of separation, and since that time the planet should have increased its rotation by cooling. Its period of rotation should therefore be shorter than the period of the satellite's revolution. Explanations have been suggested for this difficulty, but they do not meet the case. The small bodies that make up the inner edge of the inner ring of Saturn also revolve in about half the time that planet rotates.

6. If the solar system were converted into a gaseous spheroid, with its matter distributed according to the laws of gases, and expanded to Neptune's orbit, and if this nebula had the total momentum (technically, the *moment of momentum*) of the solar

system, it would not have acquired a rate of rotation rapid enough to detach matter from its equator *until it had contracted well within the orbit of the innermost planet.*

7. If the nebula were a spheroid of gas whose density followed the law of gases, and if it had a rotation rapid enough to shed rings from its equator as the theory supposes, its moment of momentum would need to have been very much greater than the system now possesses. This is at variance with the established law that the moment of momentum of such a system *must remain constant.* To separate Neptune, the moment of momentum would need to have been 200 times what it is; to separate Jupiter, 140 times; to separate the earth, 1,800 times. These are enormous discrepancies and they are not consistent with one another.

8. Comparing the masses of the planets with the moments of momenta they carried off from the parent nebula, strange discrepancies appear. The matter in the ring supposed to have formed Jupiter and his moons had a mass less than 1/1000 that of the nebula at the time of separation; but Jupiter and his moons have about 95 per cent of the total moment of momentum which the nebula then had. The Laplacian hypothesis asks us to believe that an equatorial ring, having a mass less than 1/1000 that of the parent body, carried off 95 per cent of the total moment of momentum when it separated. The supposed separation of other rings involves similar incredible ratios.

9. Under the Laplacian hypothesis, the satellites should all revolve about their planets in the direction in which the planets rotate on their axes; but the sixth satellite of Jupiter and the ninth satellite of Saturn revolve in the opposite direction.

10. Our knowledge of nebulæ has been extended greatly in recent years, but nebulæ with such rings as the Laplacian hypothesis calls for have not been found.

The force of these objections appears to be such as to make the hypothesis untenable.

2. **The meteoritic hypotheses.** It was long ago noted that shooting stars enter the upper atmosphere in great numbers, and that occasional fragments of stony and metallic matter fall to the earth. Out of this grew the notion that the earth may have been built up in this way, save that the process was more rapid in the early days of the earth's history. This notion, however simple and natural, may be dismissed without serious consideration, for

the different directions of motion and the various velocities of meteorites are such as to forbid the belief that the solar system, with its symmetrical discoidal form and its harmonious motions, could have been formed in this way.

A more logical meteoritic hypothesis is based on the conception that meteorites may be aggregated into swarms and constitute nebulæ. This hypothesis is, therefore, nebulo-meteoritic. Sir George Darwin came to the conclusion that such a swarm of meteorites would act very much like a gas, and that the laws of gases could be applied in determining its mechanics. If the meteorites of such a nebula move in various directions, this hypothesis, as applied to the origin of the earth, is practically identical with the gaseous hypothesis; and as applied to the solar system, it is subject to the criticisms already urged against that hypothesis. The term meteoritic hypothesis is used commonly in the above sense. It was applied by its authors (Lockyer and Darwin) chiefly to the earlier and more scattered conditions of the nebulæ, and has not been applied specifically to the formation of a planet. If, on the other hand, the meteorites were so assembled as to have concentric orbits and form a disk-like system, the system, to all intents and purposes, falls into class 3.

Fig. 288. A spiral nebula in Canes Venatici, Messier 51. The exposure was long and has given relative exaggeration to the fainter parts. The nucleus is apparently dense and relatively massive; the coiling is pronounced and rather symmetrical in the inner parts, but departs from symmetry in the outer parts. A notable feature is the comet-like streamers of some of the knots and denser portions. If these are true streamers, curved by motion, they imply an active rotation, and strengthen the inference drawn from the coiled condition. (Photo. by Ritchey, Yerkes Observatory.)

3. **The planetesimal hypothesis.** When the shortcomings of the Laplacian hypothesis were seen to be so serious that there was no apparent way of escape from them, an alternative better in accord with the facts was sought.

It has been shown by photography that there are a multitude of

nebulæ,— at least ten times as many as were known a few years ago,— and that in this multitude there is one dominant form, the spiral nebula (Fig. 288). The spiral nebula has a central nucleus, from which two arms or sets of arms project on opposite sides, and curve spirally outward. The arms of some nebulæ branch, and are much interrupted and knotted, and between them there is much scattered hazy matter. The prevalence of this form of nebula implies that it is due to some process which has been common. The numerous nebulous knots on the arms, and in some cases more or less outside them, are significant features. Clearly the matter of the nebula is very unequally distributed, and does not conform to the laws of gaseous distribution.

Recent advances in spectroscopy throw much light on the constitution of nebulæ. As inferred from their forms, the spiral nebulæ seem to be composed of solid or liquid particles, though gases may be present particularly in their nuclei and knots. These tiny bodies are believed to revolve about the center of gravity of the nebula, like little planets (planetesimals), but this has not yet been proved. The planetesimal hypothesis is based on a spiral nebula of this supposed organization.[1]

Fig. 289. A typical spiral nebula in Piscium, Messier 74, with very symmetrical arms, pronounced nucleus and knots, and a relatively limited amount of nebulous haze. (Photo. from Lick Observatory.)

The planetesimal hypothesis starts with a spiral nebula consisting of the following elements: (1) The main knots to serve as nuclei for the planets, (2) small scattered knots as the nuclei of asteroids, (3) other small knots near to the large ones and controlled by them, as the nuclei of satellites, and (4) scattered matter or nebulous haze to be gathered into these nuclei to give them their mature sizes, and (5) the great central mass of the nebula, forming the nucleus of

[1] The manner in which it may have arisen is discussed in the authors' larger work on Geology, Vol. II.

the sun. The gathering of the scattered planetesimals into the knots to form the planets, planetoids, and satellites is assigned to the coming together of these bodies as they pursued their slightly different orbits, not as the result of falling directly together under the control of gravity.

It is assumed that the planetesimals had rather highly elliptical orbits arranged in disk-like form. Such orbits would be favorable for the meeting and union of the bodies following them. It can be shown mathematically that under such conditions the addition of planetesimals to the nuclei would give them more and more circular orbits as the nuclei grew, and it is significant that most of the planetoids (asteroids), which presumably have grown little, have the most eccentric orbits, that Mercury and Mars, the smallest of the planets, have more eccentric orbits than the others, while the orbits of the larger planets approach circularity more closely. The photographs of spiral nebulæ show large knots with small ones near them, which appear quite capable of evolution into planets and satellites. They also show small scattered knots susceptible of forming planetoids (asteroids). The earth-moon system is assumed to have been derived from companion nuclei of very unequal sizes.

The knots might have had a rotary motion at the outset, arising from inequalities of projection at the time of their formation; but in part, the rotations of the planets are assigned to the impacts of the planetesimals as they joined the nuclei to form the planets. There would be no fixed relation between the time of rotation of a planet and the time of revolution of its satellites; the period of the latter might be longer or shorter than that of the former. Even if the revolution-period of a satellite-nucleus was originally the same as the rotation-period of the planetary-nucleus, the growth of the planet might draw the satellite nearer to itself and shorten the time of its revolution. Thus the difficulty of Phobos and of the innermost part of the ring of Saturn is obviated. The mode of accretion assigned might give rise to forward rotation or to retrograde rotation of the planets and satellites; the forward rotation should be the rule and retrograde rotation the exception, as is the case. In a spiral nebula formed in the way assigned, the outer parts of the arms should be composed of lighter materials than the inner parts, and since the planets were formed from these arms, the inner ones should have higher specific gravities than the outer ones, as is the fact. Other peculiarities of the solar system seem to find a fitting explanation

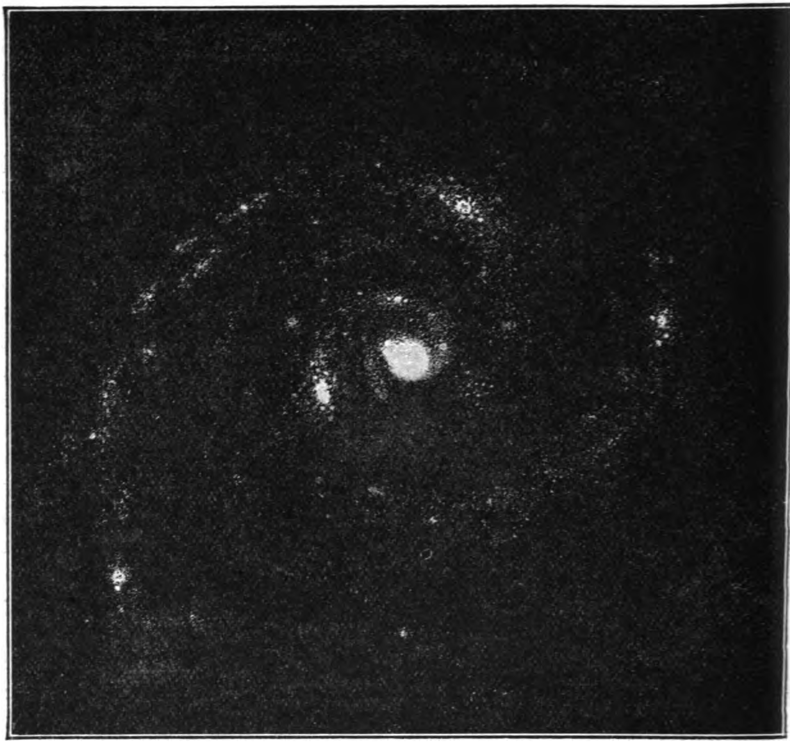


Fig. 290. Theoretical restoration of the parent nebula of the solar system. The nuclei of the several planets may be identified by their distances from the center. The dimensions of the inner parts are made disproportionately large.

in the planetesimal hypothesis, but most of these must be passed without mention here.

The assumed meetings and unions of planetesimals and nuclei at the crossings of their orbits imply a relatively slow evolution of the nebula into the solar system. The planetesimal hypothesis therefore implies a slow growth of the earth. With such a mode of growth, the stages of the earth's early history depart widely from those postulated by the Laplacian and the meteoritic hypotheses.

# CHAPTER XII

## STAGES OF THE EARTH'S HISTORY PRIOR TO THE KNOWN ERAS

The conception of the history of the earth prior to the earliest stage which can be read from the strata must depend upon the view which is entertained as to its origin. The course of its early history according to each hypothesis of its origin, will be sketched separately. Though these sketches are necessarily hypothetical, their study is important, for the great features of the earth and of the earth-shaping processes were inherited from these early stages.

### I. STAGES UNDER THE LAPLACIAN HYPOTHESIS

The hypothetical stages of the earth's early history, according to the Laplacian view have been stated as follows,[1] and they must have been essentially the same for any view of primitive conditions that involves a molten globe.

I. "The *Astral* æon, or that of the fluid globe having a heavy vaporous envelope containing the future water of the globe or its dissociated elements, and other heavy vapors or gases.

II. The *Azoic* æon. Without life.

1. The *Lithic Era:* Commencing with the earth a solid globe, or at least solid at the surface; the temperature at the beginning above 2,500° F.; the atmosphere still containing all the water of the globe (estimated at 200 atmospheres), all the carbonic acid now in limestone and that corresponding to the carbon now in carbonaceous and organic substances (probably 50 atmospheres), all the oxygen since shut up in the rocks by oxidation, as well as that of the atmosphere and of organic tissues. The time when lateral pressure for crustal disturbance and orographic work was begun; when "statical metamorphism," or that dependent on heat of a statical source — the earth's mass and the vapors about it,— began.

2. The *Oceanic Era:* Commencing with the waters condensed into an ocean over the earth, or in an oceanic depression, with finally some emerging lands, the temperature perhaps about 500° F., if the atmospheric pressure was still 50 atmospheres. The first of tides and the beginning of the retardation of the earth's rotation. Oceanic waves and currents and embryo rivers begin work about the emerged and emerging lands; the large excess of carbonic acid and oxygen in the air and water a source of rock-destruction; before the

[1] Dana, Manual of Geology.

close of the era, the formation of limestones and iron-carbonate by chemical methods, removing carbonic acid from the air and so commencing its purification; the accumulation of sediments without immediate crystallization or metamorphism, and thereby the beginning of the earth's *supercrust*.

III. The *Archæozoic* æon. Life in its lowest forms in existence.

1. *The Era of the First Plants:* Algæ, and later of aquatic Fungi (Bacteria), commencing with the mean temperature of the ocean at possibly 150° F., since plants *now* live in waters up to and even above 180° F. Limestones formed from vegetable secretions, and silica deposits from silica secretions; iron-carbonate, and perhaps iron-oxides formed through the aid of the carbonic acid of the atmosphere and water; large sedimentary accumulation, where conditions favored, thickening the supercrust.

2. *The Era of the First Animal Life:* Mean temperature at the beginning probably about 115° F., and at the end 90° F., or lower; limestones and silica deposits formed from animal secretions; deposits of iron-carbonate and iron-oxides continued; large sedimentary accumulations."

### *Difficulties*

Quite apart from the objections to the Laplacian hypothesis, stated in the last chapter, two serious questions exist relative to the stages sketched above. The one grows out of the failure to find any great formation beneath all others having the distinctive characteristics of an original crust; and the other from doubt as to the possibility of the prodigious atmosphere postulated.

**Relative to an original crust.** The theory of a molten earth carries the presumption that the liquid substance of the earth was arranged so that the heaviest matter was at the center and the lightest on the outside. As the granitoids are the lightest of the large classes of igneous rocks, the granite-like magmas should have formed the outer zone of the molten earth. The solid crust should have been light (for rock) and homogeneous, and it should have formed a stratum over the whole earth. Except at the very surface, it should have been completely crystallized, for the cooling must have been very slow, a condition favorable for the growth of crystals. No very large amount of fragmental volcanic material can be assumed to have covered the original crust if the atmosphere contained all the water of the future hydrosphere, for that would allow no steam in the molten globe to produce abundant volcanic fragments. Pyroclastic material of later times can hardly be supposed to have concealed the original crust permanently, for many thousands of feet of rock have been eroded from the surface of the oldest known areas. It is equally improbable that the original crust has been concealed *everywhere* beneath sediments derived from itself.

Until recently, the great granitoid areas of the Archean system (the oldest known rocks) were thought to possess these obvious characteristics of an original crust; but it has been found that most of them were *intruded* into rocks which had previously been formed *on an older surface* by (1) lava outflows, (2) volcanic explosions, and (3) sedimentation. This reduces to an unknown, and apparently to a vanishing quantity the rocks that can be referred plausibly to a supposed original crust. If further investigation shall finally exclude all accessible rocks from an original crust, the molten theory will have lost its observational support.

**Relative to the primitive atmosphere.** Under the Laplacian hypothesis, the primitive atmosphere has been held to have been vast, hot, and heavy, and to have contained (1) all the water of the globe, (2) all the carbon dioxide now in carbonated rocks, (3) that portion of the oxygen which has been added to the rocks by oxidation, as well as (4) that portion of all these constituents which is now found in the atmosphere and in organic tissues. The assumption back of this seems to be that heat always promotes the expulsion of gases from rock; if so, the exclusion of the gases from the rock should have been most complete in the white-hot primitive globe. The conception that the rocks after cooling re-absorb the atmospheric gases is expressed in the view, once prevalent, that the former atmosphere and hydrosphere of the moon have been absorbed into it, and in the familiar prophecies of a similar doom for the atmosphere and hydrosphere of the earth.

*Adverse evidence.* So great an atmosphere with so much carbon dioxide and water-vapor should have given the earth a warm and equable climate. Such climates indeed seem to have prevailed at certain times during the earlier parts of the earth's history, as during the later; but the studies of the past two decades have shown that there was extensive glaciation *on the very borders of the tropics*, as early as *the close of the Paleozoic*, and that there was glaciation in northwestern Europe, in China in Lat. 31°, in Australia, and perhaps in South Africa, at *the very beginning of the Paleozoic.* It is even claimed that there was glaciation in the early part of the Proterozoic long before the Paleozoic, and this claim seems likely to be made good. There seem to have been, even in very early times, much the same alternations of uniform with diversified climates that have marked later eras. The air-breathing animals of early ages, and the devices that protected the leaves of plants against too intense sun-

light and too rapid evaporation, seem irreconcilable with a vast cloudy atmosphere overcharged with carbon dioxide and water-vapor. The hypothesis of an enormous original atmosphere, suffering gradual depletion, finds, therefore, scant support in a critical study of either the biological or the physical history of the earth.

Modifications of the Laplacian hypothesis (known commonly as the Nebular hypothesis) have been suggested,[1] with a view to obviating the objections to the current form of the hypothesis as applied to the earth. But the suggested changes do not seem very satisfactory, and there is reason for thinking that all hypotheses of the earth's origin involving a molten condition of the globe, will soon be abandoned by geologists.

## II. STAGES OF GROWTH UNDER THE PLANETESIMAL HYPOTHESIS

It is possible to suppose that the earth grew up by accessions in some other mode than that of planetesimal evolution, but the latter furnishes the basis for the following sketch:

1. **Nuclear stage.** A knot of the nebula was the nucleus of earth growth. The knot may have been gaseous, or planetesimal, or both. It caught planetesimals from the nebular haze as it crossed their paths, and thus grew in mass while it was being condensed into the beginning of the earth-body. This stage lasted until the knot was condensed into a solid mass. This mass then served as the nucleus for further growth by captured planetesimals.

2. **Initial atmospheric stage.** There may possibly have been an early stage when the mass of the earth was too small to hold permanently the lighter free molecules such as form our present atmosphere. In this case the nucleus must have been made up mainly of heavy molecules such as form the stony and metallic parts of the earth; but such a stage is not probable. If the mass of the nucleus were one-tenth of that of the present earth, it would hold some atmosphere, but it would be thin and composed mainly of the heavier gases. This early thin atmosphere grew as the earth grew, by capturing molecules from the nebulous mass. The stony and metallic planetesimals also contained atmospheric material in combination or occluded,[2] and some of this, set free when the planetesimals were heated by plunging into the air or when they

[1] Vol. II of the author's three-volume Geology.

[2] The Gases in Rocks, R. T. Chamberlin, Carnegie Institution, 1908.

struck the earth, added to the atmosphere. Thus the atmosphere grew as the earth-body itself grew. Volcanoes, when they came into action, also added to the atmosphere, for they discharge much gas. This picture of the early atmosphere is very different from the vast hot vaporous atmosphere of the supposed molten earth.

3. **Initial volcanic stage.** As the earth grew and its gravity increased, its interior became more and more compressed and therefore more and more heated. Radio-active matter was no doubt gathered in with the other matter, and this developed heat. When the heat from these two sources became sufficient to liquefy the most fusible portions of the earth matter in particular spots, the fluid parts began to work their way toward the surface by fluxing. Other fusible matter was picked up on the way, and the radio-active matter in particular joined the rising threads of lava. When this rising lava reached the surface, volcanic action was inaugurated. According to this view, volcanoes do not originate from a "molten interior," or from "reservoirs" of molten matter left over from a general molten state, but the lava is generated from time to time by the continued action of radio-active substances, conjoined with the effects of compression and molecular rearrangement within the earth. The heat of the interior of the earth is thus carried outward about as fast as it liquefies the more fusible parts within its reach. Thus the interior of the earth only reaches *the temperature necessary to melt the more fusible parts*, leaving the earth as a whole solid all the time.

4. **Initial hydrospheric stage.** Water in the form of vapor is light and active, and probably was not the first gas to be held by the growing earth; but when the earth became large enough, water-vapor was held in the atmosphere, and when at length saturation was reached, it condensed into water and initiated the hydrosphere. The source of water, according to the hypothesis, was the same as that of atmospheric gases.

It may be added that the hypothesis gives a simple explanation of ocean basins and continental protuberances. Because of unequal growth, the surface of the earth may never have been perfectly spheroidal, so that when water began to accumulate on its surface, it gathered in depressions. The planetesimal material which afterwards fell into the water was protected from weathering, while that which fell on the higher land was exposed to weathering, with its attendant lessening of specific gravity. Thus the depressed areas

tended toward higher specific gravities, and hence toward still further depression when deforming stresses were brought to bear on them, while the elevated areas tended to grow relatively lighter, and to suffer relative elevation, under the stress of deformative movements. Thus the differentiation of the oceanic basins from the continental masses began as soon as the hydrosphere began, that is, long before the earth reached its present size, and has continued to the present time.

5. **Initial life stage.** Suitable conditions for life seem to have existed after an atmosphere and hydrosphere had developed to the proper extent, but it seems possible that life began long before the earth was full-grown. Under the planetesimal hypothesis, therefore, the time during which life may have existed on the earth is very much longer than the time assumed under the older hypotheses.

6. **Climax of volcanic action.** While volcanic action may have begun early, it probably had to await (1) sufficient growth to give the requisite internal heat by compression, and (2) sufficient time for the heat so developed to creep out to zones of less pressure, where it would suffice to liquefy the more fusible (soluble) parts of the rock. Vulcanism was probably hastened by radio-activity. Once begun, it is believed to have increased in importance, reaching its climax some time after the more rapid growth of the earth had ceased.

For obvious reasons, the climax of vulcanism was attended by deformations of exceptional intensity. The transfer of so much material from below to the surface required readjustment within, and the intrusion of the enormous granitic batholiths, such as are found in the early formations, was in itself a cause of deformation. Diastrophism probably had its climax with the climax of vulcanism, and both came, by hypothesis, about the time of the opening chapter of the well-recorded history of the earth. The formations of the period when volcanic action was at its height, including some contemporaneous sedimentary deposits, are regarded as constituting the oldest accessible rocks of the earth (the *Archean*), though probably only the later part of the great volcanic series is represented by the *known* Archean. It is for each student to judge whether the assigned antecedents lead felicitously or otherwise to the conditions which the oldest known rocks reveal. The value of a hypothesis, when its truth cannot be demonstrated, lies mainly in its working qualities.

7. **Gradational stage.** To complete the survey of stages, it is necessary to note that after the growth of the earth had nearly ceased, and volcanic action had passed its climax, the surface was no longer subject to universal burial, but was exposed, age after age, to the action of air and water. The material removed by these agents from the higher parts was deposited in the basins. Throughout all the remaining part of this stage, the dominant geologic processes were gradational. Vulcanism and diastrophism continued to be important, but not dominant. This stage embraces the Proterozoic and later eras.

These stages of the earth's history may be grouped as follows:

| | |
|---|---|
| III. Eon of Dominant Gradational Processes (the well known eras) | Cenozoic Era<br>Mesozoic Era<br>Paleozoic Era<br>Proterozoic Era |
| II. Eon of Dominant Extrusive Processes (transitional from the hypothetical to earliest known era) | Archeozoic Era<br>*b*) The known portion<br>*a*) The buried portion |
| I. Eon of Dominant Formational Processes (hypothetical) | Initial life stage<br>Initial hydrospheric stage<br>Initial volcanic stage<br>Initial atmospheric stage<br>Nuclear stage (Early nuclear growth)<br>Nebular stage |

# CHAPTER XIII

## THE ARCHEOZOIC ERA

Though the preceding sketches of the early stages of the earth's history are but hypothetical, they afford a helpful introduction to the study of that part of the earth's history recorded in the rocks. Figs. 291–293 represent diagrammatic radial sections which illustrate the different conceptions of the constitution of the earth. The following summary should make the figures clear:

1. According to the Laplacian hypothesis, there should be presedimentary igneous or meta-igneous rock everywhere below the prevailing sedimentary rocks of the surface. The plane of demarkation between these two sorts of rock should, as a rule, be distinct.

A modification of the Laplacian hypothesis, so far as applied to earth, postulates that much gas and vapor were occluded in the molten earth, instead of being all in the atmosphere. On this assumption, it is conceived that there might have been a period of great vulcanism after the formation of a crust, and that the original crust was covered deeply with extruded rock (Fig. 292). If this were the case, the original crust might not be accessible. On the meteoritic hypothesis of the earth's origin, the conditions would have been much as on the planetismal hypothesis so far as concerns the oldest rocks accessible.

2. According to the planetesimal theory, (1) the core of the earth (Fig. 293) is made up of planetesimal matter. After aggregation, this matter was probably re-crystallized under the influence of the heat and pressure which the aggregation involved, the resulting rock being essentially igneous in its nature. Outside the central core there should be (2) a thick zone made up largely of planetesimal matter, but partly of igneous rock erupted from below, and partly of sedimentary rocks formed at the surface at all stages of the earth's growth after the hydrosphere came into existence. The planetesimal matter is assumed to predominate in the lower and major part of this zone. Igneous rock is assumed to have a somewhat irregular distribution through it, while sedimentary rock increases in importance above, but remains throughout a subordinate constituent. This zone records the growth of the earth from the beginning of volcanic and atmospheric processes, until it reached

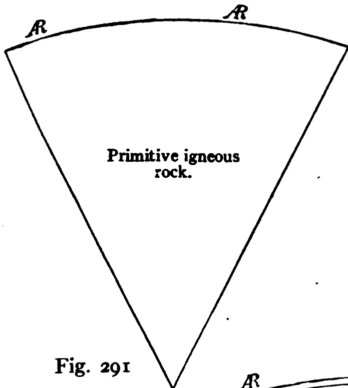



Fig. 291

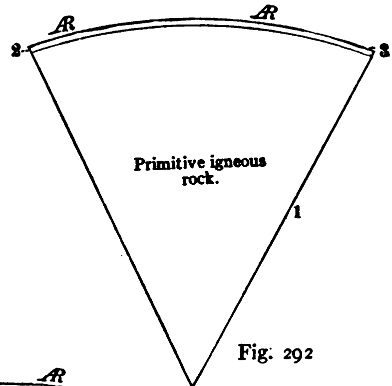



Fig. 292

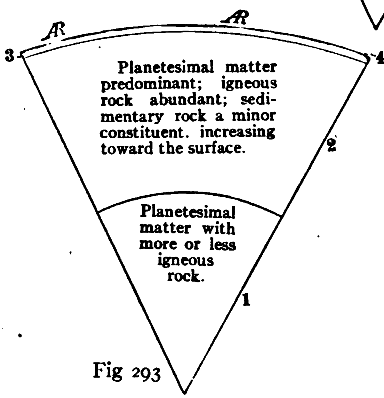



Fig 293

Fig. 291. A diagrammatic sector of the earth illustrating its structure according to the Laplacian hypothesis. The great body of the earth is made up of the original igneous rock. Sedimentary rocks, together with some extrusive rocks, make but a thin coating, represented in the diagram by black, outside the great igneous interior. The original igneous rock is represented as appearing at the surface in some places (AR). This, according to one view, might represent the Archean rock.

Fig. 292. Diagram illustrating the composition of the earth on the modified form of the Laplacian hypothesis. The great body of the earth is the original igneous rock. Outside this original igneous mass, there is a zone (zone 2) of extrusive material, with perhaps some sedimentary rock interbedded. The material of this zone is represented as coming to the surface at some points (AR). Outside this zone there is a third, made up primarily of sedimentary, but subordinately, of extrusive rocks. The material of the second zone might constitute the Archean rock.

Fig. 293. Diagram representing the structure of the earth according to the planetesimal hypothesis. The material of zones 1 and 2 is indicated in the diagram. Zone 3 of this figure corresponds to zone 2 of Fig. 292, and zone 4 of this figure corresponds to the outermost zone of Figs. 291 and 292.

nearly its present size. The central core and this thick zone about it represent the Formative Eon (p. 313). (3) The next zone, relatively thin, is assumed to be made up largely of extrusive igneous rocks, with subordinate amounts of sediment, and matter gathered from space. This zone represents the Extrusive Eon (p. 313). (4) On the outside lies the superficial zone in which sedimentary rocks predominate, though associated with not a little rock of igneous origin. This fails to cover the globe completely.

**The oldest rocks.** The deepest excavations yet made in the earth are little more than a mile deep. Because of deformation and erosion, rocks once at much greater depths are now exposed; but the maximum thickness of rocks open to observation is no more than a few miles. Definite knowledge of rock formations and structures is therefore limited to some such thickness. (1) According to the gaseo-molten hypothesis, we might hope to reach the original crust; for it is not to be supposed that this original crust is everywhere covered so deeply by material derived from it as to be inaccessible. (2) According to the modified form of this hypothesis (Fig. 292), the oldest accessible rock should be in the zone of mingled extrusive and sedimentary rocks between the original crust and the dominantly sedimentary formations above. (3) On the planetesimal theory, the oldest rocks which we might hope to reach would be those referred to the Extrusive Eon (p. 313, zone 3, Fig. 293), during which more or less sedimentary rock was mingled with the volcanic. On this hypothesis, as on the preceding, the line of demarkation between dominantly sedimentary rocks above, and dominantly non-sedimentary rocks below, would not be sharp.

The rock-formations now most widely exposed at the surface are sedimentary, and were formed during the Gradational Eon (p. 313). In many places, however, diverse formations which are predominantly extrusive (igneous or meta-igneous) are found, either beneath the prevailing sedimentary rocks, or projecting up through them in such relations as to show their greater age (Fig. 302). In many cases these lower and older rocks were thoroughly metamorphosed, and in essentially their present condition, before the deposition of the overlying beds. These dominantly igneous and meta-igneous formations, older than the oldest known dominantly sedimentary rocks, are the oldest formations known, and the era during which they were formed is the first era of which there is definite record in the accessible formations of the earth.

This lowest and oldest group of rocks is very complex, embracing lava flows, volcanic tuffs, igneous intrusions and sedimentary rocks, all more or less metamorphosed and deformed. Distinct fossils have not been found in them, but the presence locally of (1) carbonaceous slates similar to younger slates containing carbon of organic origin, and (2) occasional formations of limestone and chert, are thought to imply the existence of life, and to warrant placing the era when these rocks were formed in the zoic group of eras (p. 313). The time during which, or during the later part of which, this oldest system of accessible rocks was made, is the *Archeozoic* era.

Under the planetesimal hypothesis, the oldest known rocks may be referred confidently to the Archeozoic era, for, according to this hypothesis, rocks of organic origin and rocks containing organic products were not only mingled with all series that are accessible, but with great thicknesses of rock below, since life is supposed to have originated long before the earth acquired its present size. The oldest formations known also may be Archeo*zoic* under the modified form of the nebular hypothesis (Fig. 292); but under the original form of the hypothesis, the original crust cannot be Archeo*zoic*, since it antedated life. The term *Archean* (Archean system, Archean complex) is applied to the formations here referred to the Archeozoic era. This term is applied to the oldest group of accessible rocks, whatever their origin, and whether contemporaneous with life or antedating it.

**Delimitations of the Archean.** The bottom of the Archean system is assumed to be inaccessible. Its *upper limit* has been fixed differently by different investigators. As first defined, the Archean (very old) included all rocks below the Cambrian (p. 323); but later it became clear that the rocks below the Cambrian should be differentiated into two great groups, the upper of which consists of several great systems of dominantly sedimentary or meta-sedimentary rocks, unconformable with one another, while the lower is dominantly igneous and meta-igneous. The term Archean is now generally restricted to the latter. The upper limit of the Archean is therefore *the base of the oldest dominantly sedimentary system.*

## GENERAL CHARACTERISTICS OF THE ARCHEAN[1]

As now defined, the Archean includes two great classes of formations, (1) a great schist series, and (2) a great granitoid series.

[1] Van Hise and Leith, Mono. LII. U. S. G. S. Chapter XX, and 16th Ann. Rept. U. S. G. S., Pt. I. pp. 744-759.

(1) **The schist series** is made up chiefly of the metamorphosed products of lava flows and volcanic tuffs. In composition they vary greatly, but the dominant types are hornblende schists, other greenstone schists, and mica schists. Associated with the metamorphosed surface lavas and pyroclastic formations, there are some massive igneous rocks, and occasional beds of metamorphosed conglomerate, sandstone, shale and limestone, and beds of iron ore, all of which imply the contemporaneous activity of water.

(2) **The granitoid series.** One of the conspicuous features of the Archean system, in its present eroded condition, is the great masses of *granite* and *gneiss* that protrude through the schists. Formerly, these granites and gneisses were regarded as the oldest rocks, and were styled "primitive" or "fundamental"; but it is now known that many of them, at least, are intrusions into the schists, and therefore younger than the latter. The gneisses are regarded as metamorphosed granites.

In the formation both of the surface flows and the intrusions, the ascending lavas must have occupied numerous fissures or conduits connected with the interior; hence there are numerous dikes and other intrusions, traversing the older parts of the Archean. It is to be borne in mind also that all younger intrusions and extrusions of lava must have passed through the Archean, leaving intrusions of diverse sorts (p. 228). These later intrusions are not strictly a part of the Archean, but they are not always separable, and their presence adds to the complexity of the Archean as a whole.

**Diastrophism and metamorphism.** The most satisfactory explanation of the prevalent foliated structure of the Archean (Fig. 294) is that which refers it to the movements of the outer part of the earth in Archeozoic and later time. Intrusions of igneous rock probably aided metamorphism (1) by furnishing heat, and (2) by developing pressure. The pressure was developed in two ways, (*a*) by the intrusion itself, which developed pressure when it was intruded, and (*b*) the shifting of so much lava from below upward must have caused the outer parts of the earth to settle down to take the place of the material transferred upward.

That the rocks should have been much metamorphosed under these conditions is natural. By crushing and shearing, massive igneous rocks were given a foliated or schistose structure, and it is in the rocks of this era especially that metamorphism of this type prevails. It is now believed that the larger part of existing gneisses,

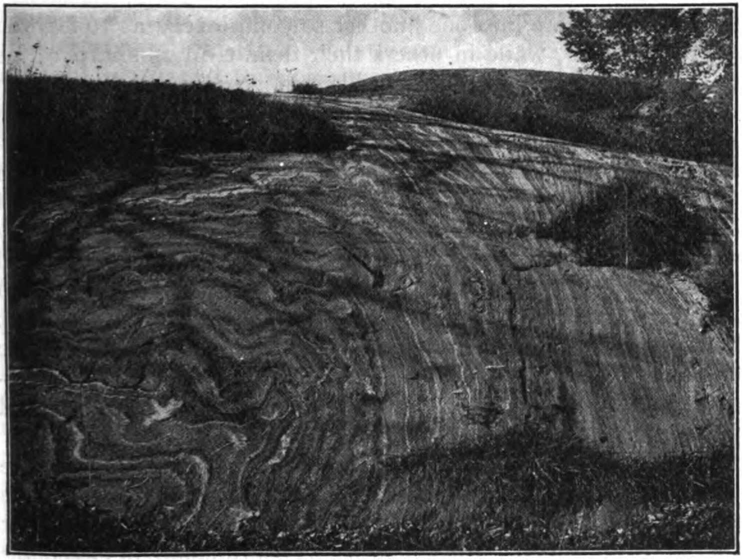


Fig. 294. **Metamorphic rock, showing foliation distinctly; bank of the Ottawa River. (Ells.)**

as well as a considerable part of existing schists, got their foliated structure in this way; but it is to be understood that some of the schists and perhaps some of the gneisses arose from sedimentary formations in other ways. It is not to be understood that the metamorphism of the Archean rocks was completed during the Archean era. The metamorphosing processes of subsequent times have affected them.

It would be difficult to obtain an exaggerated idea of the complexity of the rocks which has caused this system to be called a "complex." It consists in some places of rocks which are mainly massive (igneous intrusions); in other places, of rocks which are mainly gneissic (chiefly meta-igneous); and in still others, of rocks (largely meta-igneous and subordinately meta-sedimentary) in which a schistose structure predominates. Furthermore, the rocks of each of these structural types have a wide range in composition, from acid on the one hand to basic on the other. Rocks of all these classes are intimately associated locally, and any one may predominate over the others. In places the rocks of the several struc-

tural types graduate into one another so completely as to leave no line of separation, while in others their definition is sharp. Thus massive rock appears in distinct dikes in gneisses and schists in some places, while in others schists are in dike-like sheets in rocks which are more massive. Furthermore, the relations of these several sorts of rock have been complicated greatly by the distortion to which they have been subject. The structure and relations of the several sorts of rock in the system indicate that it was (1) by successive intrusions, large and small, of rocks of different chemical composition into (2) still older rocks which were originally (*a*) chiefly extrusive-igneous and of varying chemical composition, but (*b*) subordinately sedimentary; and (3) by successive dynamic movements resulting in various degrees of metamorphism and deformation of the various parts, that the intricate structure and composition of the Archean complex was attained.

Though the variations in the rocks of the Archean system are great, there is yet a certain homogeneity in the heterogeneity of the whole. No large part of the system is very different from any other large part, and no definite and orderly relationship between the different parts has been made out over any considerable area. There appears to be no traceable succession of beds, and no definite stratigraphic sequence, such as can be made out in great series of younger meta-sedimentary rocks.

**Earlier views concerning the Archean.** In explanation of the Archean system, many hypotheses have been suggested at one time and another, most of them starting with the Laplacian hypothesis as a beginning. One of them is that the Archean rocks are wholly of metamorphosed sediments, a second, that they are igneous rocks produced by the fusion of sediments, and a third, that they are igneous rocks intruded beneath the oldest sedimentary rocks after the deposition of the latter. These hypotheses have historic interest, but are not now generally held by geologists.[1]

## DISTRIBUTION

In speaking of the distribution of a formation, its distribution *at the surface* generally is meant, and in speaking of its surface distribution, the mantle rock (glacial drift, etc.) which overlies and conceals it is usually ignored unless it is so thick as to make the underlying formation indeterminable. When the surface distribution of the formation is given, therefore, it is not to be understood that the formation is literally at the surface everywhere within the area specified, but rather that it is exposed here and there within

[1] See the authors' Earth History, Vol. II.

that area, and that between the points of exposure it is the uppermost formation beneath the mantle rock. In this sense, the Archean rocks are estimated to appear at the surface over about one-fifth of the area of the land; but since great areas in some continents have been reconnoitered only, geologically speaking, this figure is only a rough estimate.

Concerning the real, as distinct from the surface distribution, the Archean is the one accessible rock system which, theoretically, envelops the globe completely. No later system does this, for wherever the Archean comes to the surface, later formations are necessarily absent.

*In North America*,[1] by far the largest area of Archean rock is in Canada (Fig. 295). Formations of the Proterozoic and later eras occupy numerous small tracts within the area shown on the map, though the Archean underlies them at no great depth. Lying rudely parallel to the great Canadian area on the southeast is an interrupted series of probably-Archean tracts, extending from Newfoundland to Alabama. Similarly, on the southwest, there is a belt of detached areas stretching from Mexico to Alaska. In few places within these belts have the ancient rocks been studied in detail. Lesser areas of Archean rock appear in northern Michigan, Wisconsin, and Minnesota, and in the Adirondack region, but in some of these places, Archeozoic rocks have not been carefully separated from Proterozoic. The vicinity of Lake Superior in Canada, Michigan, Wisconsin, and Minnesota, the area north of Lake Huron, and the Ottawa region in Ontario, are the areas where the system is best known.

The Archean system contains some iron ore (p. 332) and some ores of other metals, but not as a rule of great richness. Gold especially is widespread [2], but in few places is it known to occur in workable quantities.

*In other countries*, the general characters and relations of the Archean of North America seem to be duplicated. A corresponding system of rocks, made up primarily of meta-igneous rocks, but subordinately of meta-sedimentary rocks inextricably involved with them, is known in all continents. The general characteristics and relations of the Archean therefore appear to be world-wide.

[1] Van Hise, Pt. II, 16th Ann. Rept., U. S. Geol. Surv., pp. 744–843, and Van Hise & Leith, Monograph LII.

[2] Op. cit., p. 295.

Fig. 295. The white areas north of Mexico represent exposures of Archean; those of Mexico represent lack of knowledge. The black areas represent exposures of Proterozoic, and the lined areas represent Archean beneath later formations. The light shading about the borders of the land represents the continental shelves, or, what is the same thing, the area of the epicontinental seas for this continent.

## GENERAL TABLE OF GEOLOGIC TIME DIVISIONS[1]

| | | | |
|---|---|---|---|
| Cenozoic | Quaternary | Present | |
| | | Pleistocene | |
| | Tertiary | Pliocene | |
| | | Miocene | |
| | | Oligocene | |
| | | Eocene | |
| | | Transition | |
| Mesozoic | | Cretaceous (Upper Cretaceous) | |
| | | Comanchean, or Shastan (Lower Cretaceous) | |
| | | Jurassic | |
| | | Triassic | |
| Paleozoic | | Permian | |
| | | Pennsylvanian (Coal Measures) | |
| | | *Wide-spread unconformity* | |
| | | Mississippian (Subcarboniferous) | |
| | | Devonian | |
| | | Silurian | |
| | | *Wide-spread unconformity* | |
| | | Ordovician | |
| | | Cambrian | |
| | | *Great unconformity* | |
| Proterozoic | | Keweenawan | |
| | | *Unconformity* | |
| | | Upper Huronian (Animikean) | |
| | | *Unconformity* | |
| | | Middle Huronian | |
| | | *Unconformity* | |
| | | Lower Huronian | |
| | | *Great unconformity* | |
| Archeozoic | | Archean Complex | Great Granitoid Series (Intrusive in the main; Laurentian) |
| | | | Great Schist Series (Mona, Kitchi, Keewatin, Quinnissee; Lower Huronian of some authors) |

### THEORETICAL CONSIDERATIONS

**Bearing on theories of the earth's origin.** With the essential facts concerning the constitution and structure of the Archean in mind, it is in order to inquire to what hypothesis of the earth's

[1] There are many unconformities not suggested in the table, where only those which appear to be extensive are noted. Those between the systems of the Proterozoic are known to be general for the Lake Superior region only.

origin they best adjust themselves. The constitution of the system makes it clear that it does not represent the original crust of the earth or its downward extension. It cannot be affirmed, however, that no part of what is now classed as Archean is referable to an original crust; that is, it cannot be affirmed that no part of the Archean is referable to an azoic or pre-zoic period, strong as the evidence against such reference may seem. On the other hand, all the facts now known concerning the Archean adjust themselves to the planetesimal hypothesis, or to the modified form of the gaseo-molten hypothesis. They cannot, however, be said to establish either, or to preclude other hypotheses of the origin of the earth.

**Life.** The presence in the Archean system of carbonaceous material and of limestones, seems to imply the presence of life during the era of its formation. Since no fossils have been found, nothing is known of the character of the life, and little, except by inference, of its abundance.

**Duration of the era.** Of the duration of the Archeozoic era nothing can be said beyond the general statement that it was very great, a conclusion which is independent of any theory of the earth's origin. If the planetesimal hypothesis is correct, there is no readily assignable lower limit to the Archean system, and the duration of the Archeozoic era may exceed that of all subsequent time.

**Climate.** Nothing is known of the climate of the era except that it seems to have been such as to permit the existence of life, and the ordinary phases of sedimentation.

# CHAPTER XIV

## THE PROTEROZOIC ERA[1]

### FORMATIONS AND PHYSICAL HISTORY[2]

The time between the Archeozoic era and the deposition of the oldest system (the Cambrian) of rocks containing abundant fossils constitutes the Proterozoic era. It was during this era that sedimentation first became the leading process in the formation of the geological record. The composition of the sediments, now indurated, implies mature weathering, and their extent and thickness imply the prolonged deposition on low lands or in the sea, of the sediments which were the products of mature weathering. During the era several great systems of sedimentary formations were formed. With the sedimentary formations there is much igneous rock, some of which is intrusive and some extrusive.

**Stratigraphic relations of the Proterozoic rocks.** Great unconformities separate the Proterozoic rocks from the Archean below and the Paleozoic above. Great unconformities usually involve three elements: (1) a change in the attitude of the lower formation, as the result of which it is subject to erosion; (2) a long period during which its surface is eroded; and (3) the deposition of the overlying rocks on the eroded surface.

A sequence of events which might have given rise to the unconformable relations of the Archean and Proterozoic is illustrated by Figs. 296 and 297. Fig. 296 represents an area of land composed of Archean rock, subject to erosion. The sediments derived from it are deposited in the sea (at *a*). In Fig. 297, the land is represented as having sunk so as to be mostly submerged. Sediments (Al) washed down from the remaining land are being deposited unconformably on the eroded surface of *Æ*. Though widespread, the

[1] Proterozoic, as here used, is a synonym for *Algonkian* as used by the U. S. Geol. Surv.

[2] A review of the pre-Cambrian geology of North America, by Van Hise and Leith, is found in Bull. 360, U. S. Geol. Surv., 1909. This Bulletin suggests probable correlations of the pre-Cambrian of different regions, so far as now warranted.

unconformity between the Archean and the Proterozoic is probably not universal, for there are doubtless places where the surface of the Archean did not suffer notable erosion before the deposition of Proterozoic sediments upon it.

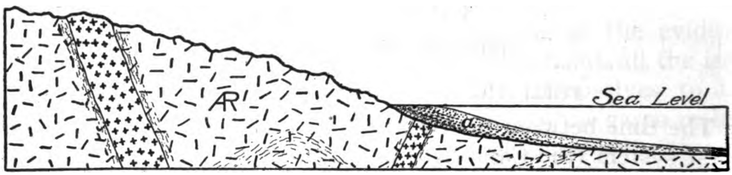



Fig. 296. Diagram showing Archean land (Æ) with sedimentation, *a*, along its borders. (Compare Fig. 297.)

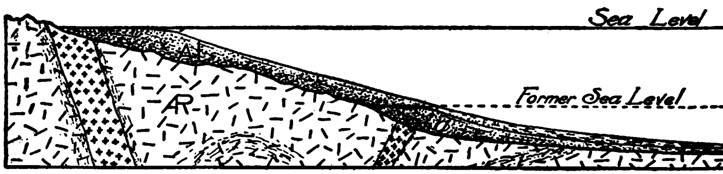



Fig. 297. Diagram representing the same region as Fig. 296, after subsidence. The *a* of this figure corresponds to *a* of Fig. 296.

**Subdivisions.** No existing classification of the Proterozoic formations has general application, but in the Lake Superior region, where these rocks are best known, four great unconformable systems are referred to this era. In some other regions the number is three (Fig. 298), in others two, and in still others but one. In most places each system is thousands of feet thick. These thick systems of

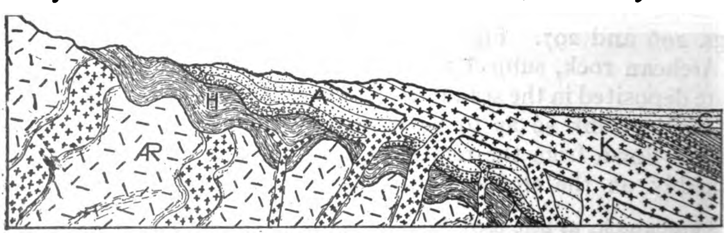



Fig. 298. Diagram showing Proterozoic where it is composed of three systems of rock in the Lake Superior region. *H*, Huronian; *A*, Animikean; *K*, Keweenawan. The diagram also shows the relation of these Proterozoic systems to the Archean (Æ) below and to the Cambrian (Ꞓ) above. The cross-pattern represents igneous rock. The lines, dots, etc., above the Archean represent sedimentary beds.

rock and the unconformities between them record the history of the era for this region.

**Proterozoic sedimentation.** The surface of the land on which the Proterozoic sediments were deposited was probably comparable to existing land surfaces of crystalline rock which have been long exposed to weathering and other phases of erosion. The topography was doubtless more or less uneven, and the surface mantled by soil and residual earths and rock debris (mantle rock) which had arisen from the decay of the underlying rock. The general nature of the clastic sediments laid down on such a surface when it became an area of deposition are readily inferred. They were made up chiefly of (1) the disintegrated products already on the surface, (2) the materials worn from the rocks by waves, if the surface was covered by the sea, and (3) river detritus.

1. One of the first effects of the Proterozoic seas, as they slowly transgressed the land — for it is presumed that this transgression was slow — was to work over, assort, and re-deposit the loose material on the surface. The coarse sediments were left in the shallow waters, while the fine materials were carried farther from shore, and left in the more quiet waters beyond. Deposits of gravel, sand, and mud were doubtless being made at the same time in different places, and changes in the position of the shore line, and in the depth of water, brought about, in time, the deposition of fine sediment on coarse, and of coarse sediment on fine. Thus the sedi-

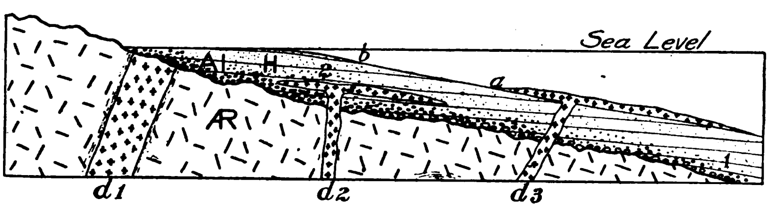



Fig. 299. Diagrammatic section showing relations which are conceived to have existed around Archean lands early in the early Proterozoic. Huronian sediments (*Al*) are in process of deposition. They are affected by intrusions and extrusions of lava, $d_1$, $d_2$, $d_3$, etc.

mentary deposits came to be arranged in beds of different sorts, coarser and finer alternating in vertical section, and grading into each other laterally.

At the base of the Proterozoic there is a widespread formation of conglomerate (Fig. 299) which appears to be composed of the

coarse parts of the mantle rock which were on the surface when the Proterozoic seas transgressed the lands of Archean rock. Such a formation is known as a *basal conglomerate*, and is one of the best indices of an unconformity.

2. Besides working over the decayed rock, the waves doubtless attacked the solid rock wherever exposures were favorable. The sediments thus acquired resembled the parent formation in average composition, and are thus distinguished from those of the preceding class, which were the products of rock decay.

3. Streams descending from the land must have brought down gravel, sand, and mud. The larger part of the river-borne detritus was probably decomposed rock, but a smaller part was doubtless derived by the mechanical action of running water on undecayed rock. Once in the sea, these several sorts of detritus were mingled.

Since some of the constituents (especially alkalies and alkaline earths) of the Archean rock dissolved during the processes of decomposition probably remained in solution in the sea-water, it is thought that the clastic sediments were more siliceous than the rock from which they were derived.

The sorting power of moving water takes account of the physical characteristics of the material handled, and not of their chemical constitution; but in the decomposition of Archean rock, the quartz remaining in the residual mantle was generally in larger particles than the clayey matter derived from the silicates, and under the sorting influence of the waves the quartz grains (sand) were more or less completely separated from the clayey parts (mud). Thus materials which were unlike chemically were separated from one another because they were unlike physically. If the Proterozoic seas had abundant life which secreted calcium carbonate, or if their waters anywhere became overcharged with calcium carbonate, limestone might have been formed.

*Extent.* Sediments accumulated in the Proterozoic era are known in limited areas only, but doubtless they were very widespread. Water-borne and wind-blown sediment must have reached all parts of the sea, and the life of the salt water probably made deposits over the whole of the ocean bottom. Some sediments, too, must have been left on land, as at all other stages of the earth's history since sedimentation began.

**The exposed formations.** The sedimentary beds of the Proterozoic consist of conglomerates, sandstones, shales, and limestones,

or their metamorphic equivalents. Before being cemented or otherwise solidified into firm rock, their materials were gravel, sand, mud, etc. The manner in which such materials are derived from older formations and transported to places of deposition, has been explained in earlier chapters.

*Basal conglomerate* is of common occurrence at the bases of the several systems of the Proterozoic. There are also conglomerate


Fig. 300. Section of the Proterozoic at a point in northern Michigan. (Æ), Archean granite. The other formations are Proterozoic. Length of section, 3 miles. (U. S. Geol. Surv.)


Fig. 301. Section showing the complex structure of the Archean and Proterozoic formations at one point in the Marquette (N. Mich.) region. *Æ gr*, Archean granite. The other formations are Proterozoic. Length of section, 2 miles. (U. S. Geol. Surv.)

beds which are not basal, and they point to changes in the conditions of sedimentation even where unconformities were not developed. *Quartzite*, composed chiefly of grains of quartz firmly cemented, occurs in thick and extensive beds. The quartz grains probably came from granitic rocks, and their separation from the other materials indicates the thorough decomposition of the rock, and ample opportunity for the rolling and rounding of the grains before they came to rest. As the quartzites of the Proterozoic are thousands of feet thick in some places, great bodies of rock must have been decomposed to furnish so much sand. There are also great beds of *shales*, or their metamorphic equivalents, which are interpreted as the clayey products of the decomposition which set the quartz free. *Limestone* is present, from which it is inferred that the sea had become calcareous by processes similar to those now in operation, and that a portion of the calcareous content of the waters was extracted and deposited.

The inference that these ancient sediments were deposited in the same manner as sediments of modern times is supported by

the ripple- and other shallow-water marks on the surfaces of the layers, and by their lamination and stratification, all of which are similar to those of sediments now being deposited.

**Geographic relations of exposed Proterozoic and Archean.** Proterozoic rocks appear at the surface in many parts of North America, but they have been clearly separated from the Archean in


Fig. 302. Diagram showing a common surface relationship between Archean (Æ), Proterozoic (*Al*), and Cambrian (€). The Proterozoic formations appear at the surface between younger and older formations.

few regions. Fig. 295 shows the area where rocks of known Proterozoic age lie at the surface, together with areas where they have not been differentiated from the Archean. In many places, the Proterozoic rocks at the surface are near areas of exposed Archean.

That the Proterozoic formations should be exposed most commonly about the borders of the Archean is made clear by Fig. 302, which shows, in section, the general relations of the Proterozoic systems (*Al*) to the Archean (Æ) below, and to younger formations (€) above. The same relations are shown in ground-plan in Fig. 303. While the relations shown in these diagrams are common, there are areas of Archean not surrounded or bordered by exposed Proterozoic formations, and areas of the latter not associated with exposed Archean. Various relations of the two are illustrated by Figs. 304 and 305.

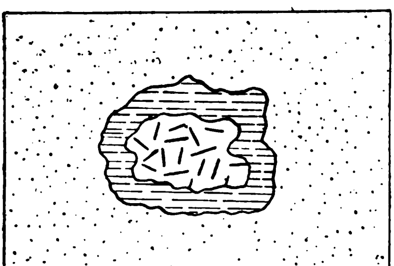


Fig. 303. Map of the formations shown in section in Fig. 302.

It is to be borne in mind that the map (Fig. 295) shows only the *exposed* areas (as now known) of Archean and Proterozoic. The Archean is presumably universal, beneath other formations. The Proterozoic is not universal, but its extent is much greater than the area where it appears at the surface. Thus the Proterozoic

of Wisconsin is probably continuous beneath younger formations with the Proterozoic of southwestern Minnesota, the Black Hills, and the Rocky Mountains on the west, and with that of Missouri and Texas on the south.


Fig. 304. Diagram showing how Proterozoic rock (*Al*) may fail to outcrop about Archean (*Æ*).


Fig. 305. Diagram showing how Proterozoic rock (*Al*) may outcrop on one side of an area of Archean (*Æ*) and not on the other.

### THE PROTEROZOIC OF THE LAKE SUPERIOR REGION [1]

The Proterozoic formations have been most carefully studied and their relations are best understood in the region about Lake Superior, and the formations of this region have become, in some measure, the standard of comparison for the Proterozoic group as a whole. The four great unconformable systems, their relations to one another, to the Archean below, and to the Cambrian above, are as follows:[2]

| | |
|---|---|
| Earliest Paleozoic | Cambrian |
| | *Unconformity* |
| | 4. Keweenawan |
| | *Unconformity* |
| | 3. Upper Huronian (or Animikean) |
| Proterozoic | *Unconformity* |
| | 2. Middle Huronian |
| | *Unconformity* |
| | 1. Lower Huronian |
| | *Unconformity* |
| Archeozoic | Archean |

### *The Huronian Systems*

The first three systems of the Proterozoic group have much in common. All are dominantly sedimentary, and each includes formations of the common sorts of clastic rock or their metamorphosed equivalents, together with limestone and beds of iron ore.

[1] Van Hise and Leith. Mono. LII, U. S. Geol. Surv.
[2] Jour. Geol. XIII, p. 161.

Since none of the limestones are known to contain fossils, their organic origin cannot be affirmed. Each of the three periods of sedimentation was long, though their duration is unmeasured. Each system contains much igneous rock, some of which was extruded while sedimentation was in progress, and some intruded later. Locally, igneous rock is more abundant than sedimentary. The unconformable relations of the three Huronian systems, and the unconformity of the third below the Keweenawan, show that after the deposition of the first, second, and third systems respectively, geographic changes occurred, resulting in erosion where sedimentation had been in progress.

The material for the sedimentary part of the first of these systems doubtless came from the exposed part of the Archean, while the sedimentary parts of the second and third systems came from the exposed parts of all older formations.

In places, the sedimentary rocks still remain in the condition of conglomerate, sandstone, and shale, though more commonly the sandstone has been changed to quartzite or quartz schist, and the shale to slate or schist. Some of the igneous rock is massive, while some of it has been changed to schist. The rocks which are least altered are, as a rule, those which have been least deformed, and in places they are still nearly horizontal, as when first deposited. The oldest system is, on the average, most metamorphosed, and the youngest least.

**Carbonaceous slates.** One of the significant formations of this region is black shale or slate, whose color is due to carbon. The carbon is thought to imply the existence of life when the sediments were deposited. Where the rocks are highly metamorphic, the black shale has been changed to graphitic schist.

**Iron ore.** Another important formation is iron ore. Here belong the iron ores of the Mesabi (Minn.), Penokee-Gogebic (Wis. and Mich.), Menominee (chiefly Mich.) and other regions (Fig. 306). The ore is in the form of ferric oxide (chiefly hematite, $Fe_2O_3$), but in this form it represents an alteration from an iron-bearing formation, originally deposited as chemical sediments, composed largely of iron carbonate and iron silicate, with some ferric oxides. These materials are believed to have been derived, directly or indirectly, from basic igneous rocks, extruded into the sea.[1] The alteration to ore was brought about at a later time, by ground-water circulating through the rocks.

[1] Van Hise and Leith. Mono. LII, U. S. Geol. Surv.

The region about Lake Superior yields more iron ore than any other area of equal size in the world. In 1913 the aggregate production of this region was about 50,000,000 long tons,[1] which was about 83 per cent of all that was produced in the United States that

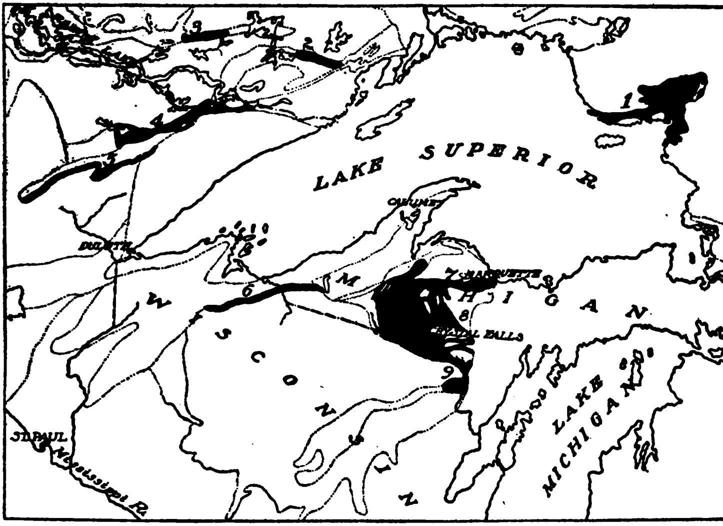



Fig. 306. Map showing (in black) the position of the iron-producing areas in the Lake Superior region. 1, Michipicoten district; 2, Kaministikwia and Matawin district; 3, Steep Rock Lake and Attikokan district; 4, Vermilion district; 5, Mesabi district; 6, Penokee-Gogebic district; 7, 8, and 9, Marquette, Crystal Falls, and Menominee districts.

year; of this, the Mesabi region produced nearly 34,000,000 tons. The ores of the Lake Superior region are partly in the Archean (about Vermilion, Minn.), partly in the older divisions of the Huronian group (about Marquette, Mich.), but most largely in the Animikean. The following table[1] gives the production in tons for the principal areas for certain years preceding 1911:

| | 1890 | 1895 | 1900 | 1905 | 1910 |
|---|---|---|---|---|---|
| Marquette...... | 2,863,848 | 1,982,080 | 3,945,068 | 3,772,645 | 4,631,427 |
| Menominee..... | 2,274,192 | 1,794,970 | 3,680,738 | 4,472,630 | 4,983,729 |
| Gogebic........ | 2,914,081 | 2,625,475 | 3,104,033 | 3,344,551 | 4,746,818 |
| Vermilion...... | 891,910 | 1,027,103 | 1,675,949 | 1,578,626 | 1,390,360 |
| Mesabi......... | ....... | 2,839,350 | 8,148,450 | 20,156,566 | 30,576,409 |
| Total........ | 8,944,031 | 10,268,978 | 20,564,238 | 33,325,018 | 46,328,743 |

[1] Mineral Resources of the United States.

**Other ores.**[1] Silver, nickel, and cobalt occur in workable quantities in the Huronian rocks at various points, especially in Canada. Rich ores of silver and cobalt (largely Lower Huronian) are found at Cobalt, Ontario, and ores of nickel at Sudbury.

**Thickness.** The thickness of the Huronian systems is hard to measure, because of their deformation; but if the maximum thickness of the individual formations of different localities is taken, their aggregate is several miles.

The following section from the Marquette region may be regarded as fairly typical for the region:

| | |
|---|---|
| Upper Huronian | Michigamme slate and schist. Several thousand feet (maximum) in thickness.<br>Ishpeming formation, largely quartzite. 1,500 feet (maximum) thick. |
| Middle Huronian | Negaunee formation or series (slate, schist, jaspilite, iron ore, etc.). 1,500 feet (maximum) thick.<br>Siamo slate. 1,200 feet (maximum) thick.<br>Ajibik quartzite (in places schistose). Nearly 1,000 feet (maximum) thick. |
| Lower Huronian | Wewe slate (including some other sorts of rock). More than 1,000 feet (maximum) thick.<br>Kona dolomite (some clastic beds). More than 1,300 feet (maximum) thick.<br>Mesnard quartzite. Several hundred feet (maximum) thick. |

## *The Keweenawan System*

**Constitution and thickness.** In some parts of the Lake Superior region a fourth system of pre-Cambrian rocks, the Keweenawan, overlies the Upper Huronian. Unlike the Huronian systems, it is composed more largely of lava-flows than of sedimentary strata.

The lava beds of the Keweenawan constitute its lower and larger part. The earlier flows of lava seem to have occurred on land, and to have followed one another at short intervals, for the surface of one flow was not eroded much before the next overspread it. Later, the intervals between flows appear to have been longer, and thin beds of sediment were deposited between successive sheets of igneous rock. The sedimentary beds increase in importance upward until, in the upper part of the system, lava beds fail altogether. In the valley of the St. Croix River, in northwestern Wisconsin and the adjacent parts of Minnesota, there are said to be 65

[1]Van Hise and Leith. Monograph LII, U. S. G. S., pp. 591–6.

lava-flows and 5 conglomerate beds in succession, with neither top nor bottom of the system exposed.

The igneous rocks of the system consist principally of gabbros, diabases, and porphyries; but other varieties are also present. The sedimentary rocks, chiefly sandstone and conglomerate, were derived largely from the igneous, and their character is such as to indicate that they accumulated rapidly. The thickness of the sedimentary beds has been estimated at some 15,000 feet; but there is reason for questioning the interpretation of such figures.

The total thickness of the Keweenawan system has been placed as high as 50,000 feet. Interpreted in the simplest way, this would seem to mean either that beds of rock were piled up nearly 10 miles high on land, or that they filled a basin some 10 miles deep. Since the upper part of the system is sedimentary, and sediments do not

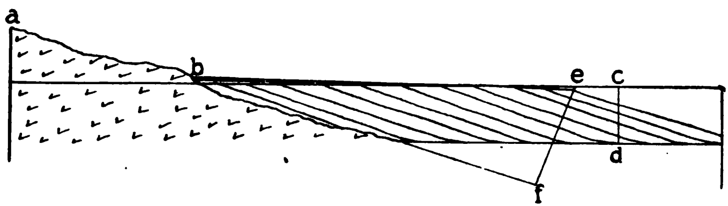



Fig. 307. Diagram of a series of beds formed on the abysmal slope of a continent, or in some similar situation, showing that the thickness, as usually measured, *ef*, is not dependent on the depth of the basin, *cd*, and that a thick series does not necessarily imply subsidence, even when the exposed portions of it show evidences of shallow-water deposition at various horizons.

accumulate in quantity in high places, the first of these suggestions cannot be entertained, and it is extremely unlikely that there ever was a basin 10 miles deep.

The thickness of great bodies of stratified rock is commonly measured as suggested by Fig. 307. The dip of the rock (p. 275) and its extent at the surface are measured, and the depth is then calculated on the principle that the thickness of the whole is equal to the thickness of all its parts. The thicknesses of the several beds, added together, is shown in the diagram by the line *ef*, whereas the actual thickness, from top to bottom, is shown by the line *cd*.

The point may be illustrated in another way. On the outer slopes of continental shelves, and in deltas, sediments are laid down with a considerable angle of slope. If the Amazon were to build a delta out 200 miles, the present ocean bottom remaining at an

average depth of four miles below the surface, and if the angle of deposition were 2°, the computed thickness of the deposits, according to the common methods of measurement, would be about 7 miles. If the delta were built out 1,000 miles, the computed depth would be 35 miles, though the basin was but four miles deep. If a delta were built half-way across a lake basin 100 miles wide and 1,000 feet deep, the angle of deposition being 3°, the thickness of the series, measured by the above method, would be 13,800 feet, though the basin was but 1,000 feet deep. With these points in mind it is clear that caution must be used in interpreting the great thicknesses sometimes assigned to sedimentary systems.

The sedimentary part of the Keweenawan system has commonly been assumed to imply marine submergence; but so far as now known the sediments may have been accumulated in an interior basin, or may be partly subaërial.

Fig. 308. Diagram illustrating the development of the Lake Superior syncline. *Æ*, Archean; *H* and *A*, Huronian and Animikean; *K*, Keweenawan. (Irving, U. S. Geol. Surv.)

**Deformative movements.** About the close of the Keweenawan period, the rocks of the system were somewhat deformed, and the deformation in the Lake Superior region was perhaps contemporaneous with deformation in other parts of the continent. These changes are regarded as marking the beginning of the end of the Proterozoic era. As a result of these deformations, some parts of the area where Keweenawan sediments had been deposited were brought into such an attitude as to be eroded, but the changes did not, as a rule, involve great folding or faulting of the strata. In keeping with their structure, the rocks are not greatly metamorphosed.

After the warping which followed the deposition of the Keweenawan system, the exposed surfaces of this and older systems suffered protracted erosion. Ultimately the land about Lake Superior sank again, and when the sea came back, a new series of sedimentary beds was deposited unconformably on the eroded surface of the older. The waters of the returning sea teemed with life, for the formation then made contains abundant fossils. This abundantly

fossiliferous formation is a part of the Cambrian system, the oldest system of the Paleozoic group.

**Copper.** The Keweenawan system contains the most extensive deposits of native copper known. The metal occurs in pores and cracks of the igneous rock, and between the pebbles and grains of some parts of the sedimentary beds. In the conglomerate at some of the richer mines, the copper is so abundant as to be an important cementing material of the rock. The copper is believed to have been deposited by magmatic waters (*i. e.*, waters of lavas), and to a lesser extent by thermal ground waters which had dissolved the metal from the igneous and sedimentary rocks.[1]

In 1875 the Keweenawan formation of northern Michigan yielded 16,089 tons of copper, about 90 per cent of all that was produced in the United States. In 1911 the same area yielded 109,093 tons, but this was only about 20 per cent of the copper produced in the country that year.

The ores of silver, cobalt and nickel in the Huronian formations are to a large extent at least associated with basic igneous rocks, perhaps of Keweenawan age, intruded into Huronian rocks.

### *General Considerations Concerning the Lake Superior Proterozoic*

**Duration of time.** It is difficult to conceive of the great lapse of time involved in the history of the Proterozoic era. The estimates give an aggregate thickness of more than 30,000 feet for the sedimentary rocks of the Proterozoic systems. The accumulation of so much sediment would in itself mean a vast lapse of time, and when it is remembered that the four systems are separated from one another by unconformities, each of which may represent as much time as that involved in the accumulation of a system, it will be seen that the duration of the Proterozoic era was exceedingly long, possibly comparable to all succeeding time. It would appear that it should be spoken of in terms of tens (at least) of millions of years, rather than in terms of a lesser denomination.

**Destruction of rock implied.** Thick beds of sediment mean the destruction of a still larger volume of older rock, for much of the more soluble part of the rock destroyed does not appear in the sedimentary formations. Had the Archean lands in the vicinity of

[1]Van Hise and Leith, Mono. LII, U. S. Geol. Surv. For earlier discussions, see Irving and Van Hise, Mono. V, U. S. Geol. Surv., Chamberlin, Vol. I, Geology of Wisconsin.

Lake Superior been high enough at any one time to furnish the thick sediments of the Proterozoic, their height would perhaps have surpassed any existing elevation; but it is not probable that such elevations existed at any time. It is more probable that as erosion proceeded, the land reacted by rising slowly, or that the sea bottom sank, drawing off the waters and leaving the land *relatively* higher. In this way, degradation and elevation may have been in progress at the same time, and the one process may never have got far ahead of the other. The doctrine that the surface of the lithosphere sinks and rises under increase and decrease of load is one phase of the general theory of *isostasy*.

**Succession of events.** Reviewing the succession of events in the Lake Superior region, we find (1) that land composed of Archean rocks suffered prolonged erosion, but that the sites of the earliest post-Archean sedimentation are unknown. (2) The land then sank or was so eroded or deformed as to permit the deposition of the Lower Huronian sediments on parts of its eroded surface. (3) Areas including Archean and Lower Huronian rocks then came into such an attitude, presumably by crustal warping, that they were subject to a long period of erosion, with contemporaneous sedimentation elsewhere. During the deformation, the rocks involved were somewhat metamorphosed. (4) Again the land seems to have sunk, allowing the sea (conditions for deposition) to cover a large part of the area which had been subject to erosion just before, and to deposit upon its eroded surface the sediments of the Middle Huronian system. (5) After this long period of sedimentation, certain tracts seem to have emerged, exposing the landward border of the Middle Huronian system, and the older rocks not covered by it, to erosion. This emergence of areas of Middle Huronian sedimentary formations was accompanied by some deformation and metamorphism. (6) This period of erosion was followed by another period of submergence, when sediments (the Animikean) were laid down again in the Lake Superior region, this time on the eroded surface of the Middle Huronian or some older system. (7) Deformation, accompanied by emergence and followed by erosion, succeeded this third period of Proterozoic sedimentation. (8) Flows of lava of great magnitude were then poured out upon the surface of the land over considerable areas, and intruded into older terranes. Before they ceased, sedimentation began again in the region, and soon predominated, the lavas and sediments making the Keweenawan system.

(9) After the deposition of this system, much of it was exposed to erosion.

This succession of events implies repeated changes of relative level of land and sea in the Lake Superior region during the era. We shall see that such changes are confined neither to this time nor to this region. Changes in the relations of sea and land are among the notable events of the earth's history, even to the present time. Since many other changes are dependent on them, they are believed to furnish the best basis for the subdivision of geological history. It is not now possible to determine the extent of the crustal oscillations which took place during this era; but enough is known of the extent of land in North America at the close of the Proterozoic to make its representation on maps instructive (the white areas north of Mexico, Fig. 295).

**Metamorphism.** The lower rocks of the Proterozoic are, on the whole, more highly metamorphosed than those above, but the Animikean beds are locally as highly metamorphic as the Lower Huronian, indicating intense dynamic action, at least locally, after the deposition of the third great system. Since different sorts of rock behave differently under dynamic action, it follows that some beds are much more highly metamorphic than others associated with them, even though subjected to the same forces.

There is scarcely a phase of metamorphism which the Proterozoic rocks do not show. The schists, slates, and gneisses are especially the product of dynamic metamorphism; the quartzites are the products of extreme consolidation by cementation; the iron ore is the product of aqueous metamorphism, effected by ground-waters, while other phases of metamorphism are due to the heat of intruded rock. It is not to be understood that the metamorphism of any considerable body of rock is effected by any one process alone. Dynamic action, which seems on the whole the most important factor in metamorphism, always generates heat, and high temperature, especially in the presence of water, facilitates chemical and mineralogical change. So, too, in the case of igneous intrusions, there may be great dynamic action as well as great heat, and water, an agent of chemical change, is always present.

**Events elsewhere.** A series of events consonant but not necessarily identical with those of the Lake Superior region was probably in progress about every other area of Archean rock, during the Proterozoic era; but it does not follow that about every other

Archean land area four great systems of rocks were laid down during this long era. About some such areas there may well have been one, two, or three systems of Proterozoic rocks instead of four, while about others, continuous sedimentation may have been in progress from the first of the Huronian periods to the end of the Keweenawan.

### PROTEROZOIC ROCKS IN OTHER REGIONS

Pre-Cambrian sedimentary formations occur in many other parts of North America, in relations to the Archean similar to those already described. On the whole, they resemble the rocks of the Proterozoic systems about Lake Superior as closely as could be expected under the general principles set forth.

Some of the more important occurrences of Proterozoic rocks outside the Lake Superior region are the following: (1) in an extensive area north of the Great Lakes; (2) in the eastern provinces of Canada; (3) in the Adirondacks; (4) in isolated patches in the Mississippi basin, in Wisconsin, northwestern Iowa and adjacent parts of Minnesota and South Dakota, in the Black Hills of South Dakota, in southeastern Missouri, and in Oklahoma; (5) in Texas; (6) in the Piedmont belt of the eastern part of the United States; and (7) at various points in the Cordilleras (Fig. 295).

In some of these localities, the rocks are chiefly sedimentary or meta-sedimentary, while in others they are partly or even largely igneous. Thus in the Black Hills, the Proterozoic rocks consist of slates, quartzites, schists, etc., intruded by granite. From the granite intrusions, the largest of which is eight or ten miles long and nearly as broad, numerous dikes penetrate the clastic beds, and furnish good illustrations of the metamorphosing effects of igneous intrusions. In the Adirondack region, pre-Cambrian rocks make up the larger part of the mountain mass. They include both sedimentary (meta-sedimentary) and igneous rocks, the latter partly at least intrusive in the former.

**The Cordilleran region.** The cores of many of the older mountain ranges of the west are believed to be of Archean rock. In many of them there are thick series of sedimentary or meta-sedimentary rocks (Proterozoic) overlying the Archean and surrounding its outcrops, overlain in turn by Cambrian or younger strata. Sedimentary formations predominate among these Proterozoic formations, but are associated with igneous rocks which are in part

contemporaneous. In most of these localities the Proterozoic rocks are unconformable beneath overlying formations, and above the Archean where that is shown. In much of the northwest, however, there is conformity between the Proterozoic and the Cambrian, according to present interpretations.

In the Canyon of the Colorado, pre-Cambrian formations are well exposed. The Proterozoic (Grand Canyon) group, more than 10,000 feet in thickness, rests unconformably on the Archean, and is in turn covered unconformably by the Cambrian. Here, as in Montana, a few fossils have been found.

**In the eastern part of the United States.** There are large areas of metamorphic rock in the eastern part of the United States, formerly classed as Archean. Their position is shown in Fig. 295. These metamorphic rocks include some that were sedimentary, and some that were igneous. A part of them are probably Proterozoic, but the Proterozoic, Archean, and metamorphic Paleozoic rocks have not been fully differentiated.

**Summary.** While the correspondence of the Proterozoic rocks in these various regions with those of the Lake Superior region is not generally very close, it may be pointed out again that close correspondence is not to be expected, even if the rocks of different localities were contemporaneous in origin. The phases of sedimentation taking place about any land mass at any time depend largely on the height of the land, the exposure of its coasts, climate, and the character of the formation suffering erosion. These various factors were as likely to be dissimilar as similar about the various centers of sedimentation. Igneous rocks form a not inconsiderable part of the Proterozoic systems, and there is no apparent reason why igneous activities in different regions should correspond either in time or in the nature of their products. Even deformations of the crust, which are the basis for the separation of the rocks into systems, need not have been the same in different regions. It follows (1) that the number of Proterozoic systems bounded by unconformities may not be the same in all regions; (2) that the thicknesses of the various systems may vary greatly; (3) that there need have been no close correspondence in the sorts of rock in different regions at the outset; and (4) that they may have been metamorphosed unequally since their deposition. Dissimilarity of the Proterozoic in different regions was, therefore, to have been anticipated.

### *Proterozoic Formations in other Continents*

Proterozoic formations are believed to exist in all continents. In more than one country where they have been studied, the pre-Cambrian sedimentary rocks are thought to belong to at least two unconformable systems. In Sweden, as about Lake Superior, iron ore occurs in these formations, and the great bodies of iron ore in Brazil probably are of similar age.

## LIFE DURING THE PROTEROZOIC ERA

The presence of a few fossils in the Proterozoic rocks proves the existence of life during this era.[1] The best-preserved fossils are arthropods (p. 686) resembling crustacea. There are also tracks of two genera of worms. In addition, there are obscure forms which appear to be referable to brachiopods and pteropods. It is significant that the oldest definite fossils yet found are forms well up in the animal kingdom, and that they occur (in Montana) 9,000 feet below the unconformity between the Proterozoic and the Cambrian. Other lines of evidence indicating life are: (1) Carboniferous shales, slates, and schists, and (2) limestone, some of which occurs near the base of the Lower Huronian. This rock was formerly regarded as demonstrative of the existence of life; but in recent years the belief has gained ground that considerable formations of limestone may have originated by precipitation from sea-water. This origin is suspected for many limestone formations which are free from fossils, and if the hypothesis is applicable to any extensive formation of limestone, it may be applicable to that of the Proterozoic. But even without reliance on this sort of rock, the occasional fossils leave no doubt of the existence of life in this era.

## CLIMATE

Since inferences concerning the climate of any period are drawn largely from fossils, and since fossils are exceedingly rare in the Proterozoic strata, they afford little warrant for conclusions concerning the climate of the era as a whole. Conglomerate beds which have been interpreted as glacial[2] are found at the base of

[1] For summary of knowledge concerning pre-Cambrian fossils, see Walcott, Bull. Geol. Soc. Am., Vol. 10, pp. 199–244.

[2] Coleman, Jour. Geol., Vol. XVI, pp. 149–158, and Wilson, Ibid., Vol. XXI, pp. 121–141.

the Proterozoic in the vicinity of Cobalt, Ontario. This interpretation, long doubted, now appears to be warranted. It may be noted that glacial formations are singularly out of harmony with the conceptions of the climate of early geologic time which have prevailed until recently. They are altogether in harmony with the conceptions of climate which grow out of the planetesimal theory.

*Map studies.* Map studies should be carried on in connection with the chapters on the Archeozoic and Proterozoic. For this purpose, numerous folios of the U. S. Geological Survey are especially serviceable. See also *Laboratory Exercises in Structural and Historical Geology*, Salisbury and Trowbridge, Exercise VII.

# THE PALEOZOIC ERA

## CHAPTER XV

### THE CAMBRIAN PERIOD

#### FORMATIONS AND PHYSICAL HISTORY

The crustal movements which closed the Proterozoic era converted a large area within the limits of North America into land. This is shown by the distribution of the basal strata of the Cambrian, the oldest system of the Paleozoic era. Where accessible, the base of the system is, in most places, unconformable on underlying formations. The distribution of the successive parts of the system discloses the relations of sea and land throughout the period, for most of the strata are of marine origin.

*Subdivisions*

The Cambrian system is divided into three parts, the Lower, the Middle, and the Upper. Georgian (Vt.), Acadian, and Potsdam or Saratogan (N. Y.), names of localities where the several divisions of Cambrian were first differentiated in North America, are synonyms for Lower, Middle, and Upper Cambrian respectively. The name St. Croixan (Wis.-Min.) also is used for the Upper Cambrian.

**Lower Cambrian.** Lower Cambrian formations are known in North America only near the eastern and western borders of the continent (Fig. 309). In the east, they occur in the Appalachian belt and at some points farther east; in the west, they are found in various states between the 110th and the 120th meridians. Both east and west, the strata contain marine fossils. Those of the east were accumulated in straits, sounds, etc., rather than on the shores of the open sea. The great tract between the Appalachian Mountains on the one hand, and western Montana and Utah on the other, is believed to have been land during the early part of the period, and from it sediments were probably carried to the sea on either hand.

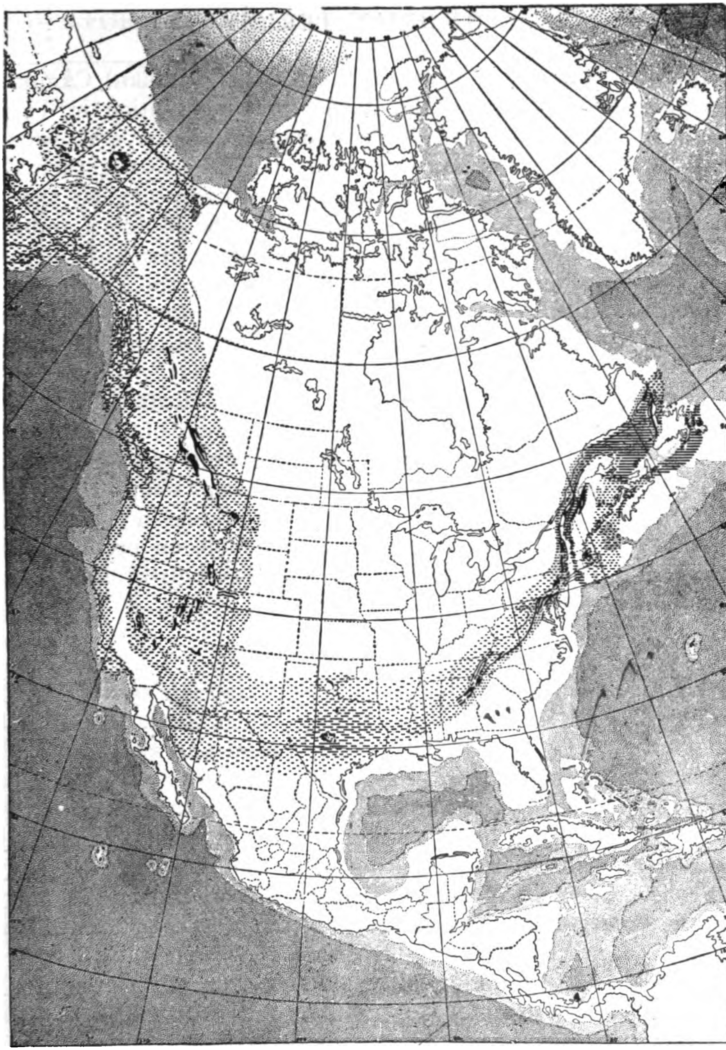


Fig. 309. Map showing the outcrops (in black) of Lower and Middle Cambrian formations. The areas shaded by lines represent regions where the formations are believed to exist, though not exposed. The longer the lines, the better the basis for belief in the existence of the beds. The unshaded areas north of Mexico are believed to have been land during the early portion of the Cambrian period. The unshaded area south of the United States represents lack of knowledge. The shading within the area of the ocean is the same as in Fig. 295. The Middle Cambrian may be somewhat more extensive than the map shows. The area not covered by the early Cambrian formations, and probably a still larger area, was land at the end of the Proterozoic.

**Middle Cambrian.** Strata of the Middle (Acadian) Cambrian are found above those of the Lower, and in addition in Texas, Oklahoma, Arizona, parts of Montana, and perhaps elsewhere. Since the Middle Cambrian beds contain marine fossils, their distribution indicates that the continent was being invaded by the sea from the south and west before the close of the Middle Cambrian epoch. Middle Cambrian beds are absent from much of the interior, if present identifications are correct. Where the Middle Cambrian rests on the Lower, the two are generally conformable. Where the Middle overlaps the Lower, it is unconformable on older formations.

**Upper Cambrian.** In the Later Cambrian (Potsdam, Saratogan, or St. Croixan) epoch, the sea overspread much more of the continent, for the Potsdam series covers not only the eastern and western borders of the continent, but much of the interior as well. The Upper Cambrian is, as a rule, conformable on the Middle in the east and west, but in the interior it is unconformable on pre-Cambrian formations. Fig. 310 shows something of the distribution of the Cambrian system as a whole.

### *Basis for the Subdivisions*

We have now to inquire how the Cambrian system may be recognized, and further, the means by which the Lower, Middle, and Upper parts may be distinguished from one another.

**Superposition.** Where a formation or series is conformable on another of known age, as the Middle Cambrian on the Lower, the presumption is that the upper was formed immediately after the lower. In this case, the approximate age of the upper is known. But where one formation is unconformable on another of known age, the stratigraphic relations between them do not show whether the upper is much or little younger than the lower.

**Fossils.** The Cambrian is the oldest system of rocks known to contain abundant fossils. Most of them represent the shells, other hard parts, or tracks of marine animals buried in the sands and muds when they were deposited. The fossils of any division of the Cambrian system constitute the known *fauna* of that stage, but it is not supposed that fossils of all species that lived have been preserved.

The Lower Cambrian formations contain certain fossils which are distinctive. Among them are species of a genus of trilobites

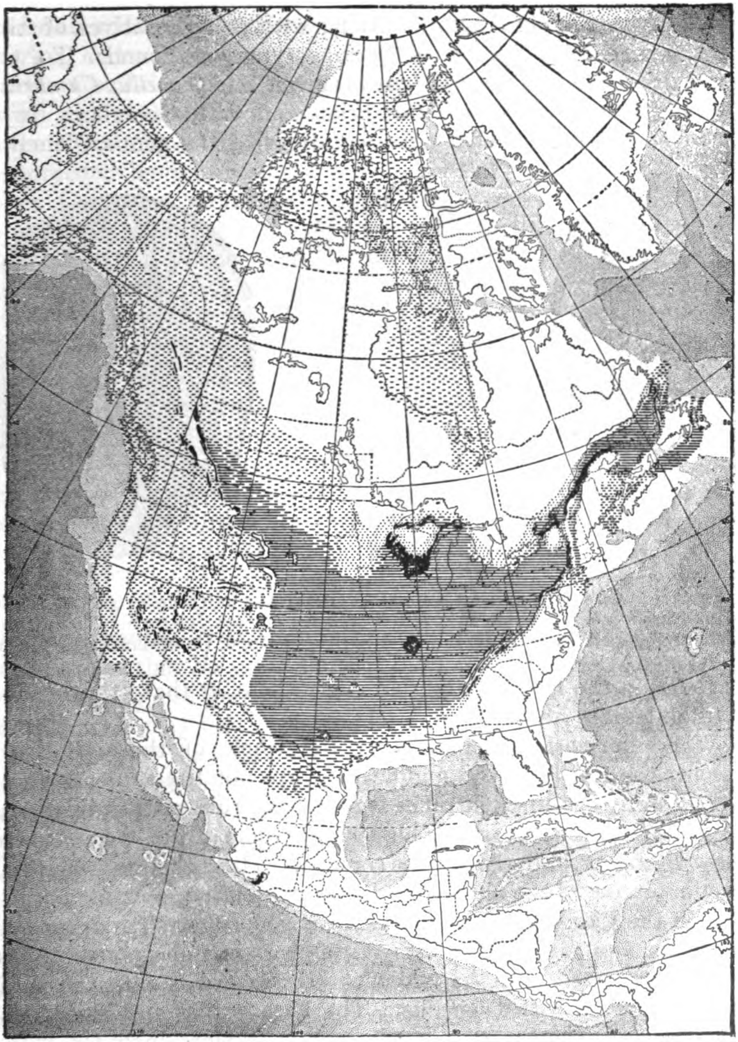


Fig. 310. Map showing the Upper Cambrian formations. The outcrops are shown in black. The continuous lines represent areas where the Upper Cambrian formations are confidently believed to exist, though concealed. The dashes represent areas where there is some reason for believing them to exist. The dotted areas represent areas from which the Upper Cambrian is believed to have been removed by erosion. The unshaded areas have the same meaning as in Fig. 309.

named Olenellus (Fig. 311, *a*). Along with representatives of this genus, many other species of various types are found. To the aggregate, the name *Olenellus fauna* is given, and *Olenellus Cambrian* is synonymous with Lower Cambrian and with Georgian. It is not to be understood that representatives of the genus Olenellus

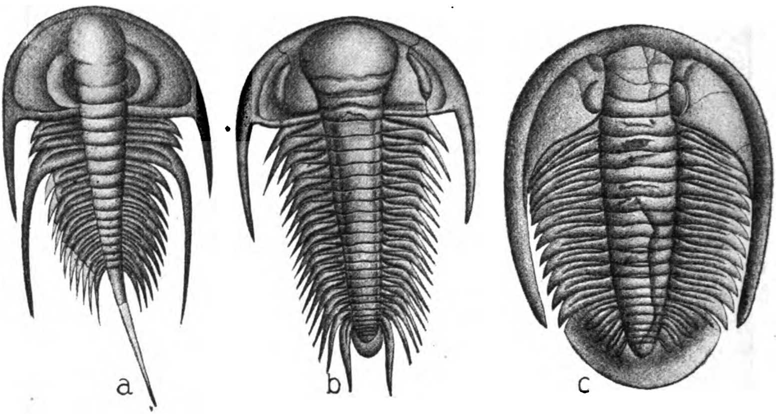



Fig. 311. CHARACTERISTIC CAMBRIAN TRILOBITES: *a*, *Olenellus gilberti* Meek; *b*, *Paradoxides bohemicus* Boeck; *c*, *Dikellocephalus pepinensis* Owen. These three genera are characteristic of the Lower, Middle and Upper Cambrian, respectively.

are found in the Lower Cambrian everywhere, or that other genera of trilobites are absent.

Where formations representing the whole of the period are present, the fossils in the middle beds are not the same as those in the lower. At no single plane is there, as a rule, a striking change in species, but in successively higher beds some of the species found below disappear, and new species come in. These changes show that the inhabitants of the sea changed as time went on. At about that stage in the Cambrian system where the genus Olenellus drops out, the genus *Paradoxides* (Fig. 311, *b*) appears in some places. The species associated with Paradoxides are somewhat different from those associated with Olenellus. The Paradoxides and their associates constitute the *Paradoxides fauna*, which includes many species of other genera of trilobites, and many species not related to trilobites. By general agreement, the Middle Cambrian, on both sides of the North Atlantic, is defined by the Paradoxides fauna, so that *Paradoxides Cambrian* is synonymous with Middle

Cambrian and with Acadian (p. 344). In the western part of North America, and on the opposite side of the North Pacific as well, the Middle Cambrian does not contain Paradoxides. Its fauna is known as the *Olenoides fauna*, which is distinct from fauna of the Lower Cambrian. In like manner the Middle Cambrian fauna is succeeded by another, the *Dikellocephalus fauna* found in the Upper Cambrian strata. Geologists have agreed to define the Upper Cambrian as the series of strata carrying this fauna.

It is not to be understood that every species of the Paradoxides fauna is unlike every species of the faunas below and above. This is not the case; but so many species of the three faunas are different, that with a considerable number to judge from, their separation is possible by those familiar with Cambrian fossils.

**Sequence of faunas based on stratigraphy.** The sequence of faunas was first determined *by superposition of the strata.* The Lower Cambrian fauna could not have been known to be older than the Middle Cambrian fauna if beds containing the former did not underlie beds containing the latter. In other words, *the primary basis for correlation by means of fossils is stratigraphy.*

### *Physical Events of the Cambrian*

**Submergence.** The distribution of the several series of the system shows that *the great physical event of the Cambrian period in North America was progressive submergence of the continent.* Theoretically, this may have been brought about by a rise of the sea or by a lowering of the land, or by both together. Both the lowering of the land and the rise of the sea may be due to gradation, to diastrophism, or to the two combined.

*Gradation as a cause of submergence.* Gradation is perpetual and inevitable where land and sea exist. The waves attack the land along its borders, and the agents of land degradation lower its surface. The former is a direct cause of encroachment of sea on land, and the latter is an indirect cause, since all sediments carried from land to sea raise the surface of the sea correspondingly. Small as this rise is for any brief period, its effect is to cause the sea to advance on the land, and the lowering of the land by degradation at the same time increases the area of the advance. *If continued long enough,* shore-cutting about the borders of the lands, downcutting over the whole surface, and the accompanying rise of the sea-level, must inevitably cause the water to cover the continents

*provided there is no deformation of the body of the earth in the meantime.*

If the earth were to remain without deformation long enough for the continents to be base-leveled, the deposition in the sea of the sediments thus derived would raise the water about 650 feet. This would submerge a large part of the base-leveled land. The evidence of gradation in the Cambrian period is clear and firm. Most of the sediments which make up the Cambrian system of rocks were eroded from the land and deposited in the sea. This lowered the land and raised the sea. Gradation was, therefore, a factor in the submergence of the continent, and there is evidence that great progress was made toward base-leveling before the close of the period.

If gradation were the *sole* agency involved in the submergence of the lands, the advance of the sea should have been steady, though not necessarily equal in rate at all times and places. Without going into details, it seems certain that there were changes in the areas of deposition other than those which can be accounted for by gradation, but none of these changes imply notable warpings such as are recorded in the rocks of the Proterozoic and Archeozoic eras.

*Deformation as a cause of submergence.* Deformations which may cause submergence of land (and emergence of sea-bottom) are of various sorts. Any deformation which causes the land to sink, or the sea to rise, leads to submergence. Such movements and their causes have been discussed briefly (chapter VIII). One special phase of movement which may have especial significance here is noted at this point.

*Continental creep.* The continents are about 15,000 feet above the ocean bottom. Their weight causes an average pressure of 15,000 to 20,000 pounds to the square inch on their bases, 15,000 feet down. This pressure *tends to cause the continents to spread by creep into the ocean basins*, on the same principle that an ice-sheet spreads. Spreading is opposed by the hydrostatic pressure of the oceans against the sides of the continental platforms. This is some 5,000 pounds per square inch at the bottom, so that there remains an unbalanced pressure of 10,000 to 15,000 pounds per square inch, tending to cause creep. Is this enough to overcome the strength of the rock, which opposes creep? Even the lesser of these figures is equal to the crushing strength of some of the weaker rocks, and is a notable percentage of the crushing strength of even the strongest. Under less pressure

than this, rock in some mines is observed to creep. It is not improbable, therefore, that such a pressure, constantly exerted for a prolonged period, might cause some spreading of the great continental platforms, and hence (1) some lowering of their surfaces, (2) some submergence about their borders, and (3) at the same time some rise of the sea-level. Many phenomena which cannot be cited here seem to lend support to this hypothesis of lateral creep,[1] but its efficiency is not determined.

### *Sedimentation in the Cambrian Period*

Sedimentation in the Cambrian period appears to have followed the general laws that govern deposition in periods of comparative freedom from great deforming movements. Most of the known sediments were deposited in the sea, and their area may be regarded as a rough measure of the area of the Cambrian sea. Sedimentation was probably faster in the early stages of the period when the land-area was largest and highest, and slower in the later stages after the land had been lowered and narrowed. Sedimentation was probably greatest near the land.

**Sources and kinds of sediments.** As in other periods, the land-derived sediments came from all formations exposed to erosion. The sediments along the immediate borders of the land were doubtless different from those farther out, and even along shore probably there were variations, because of differences (1) in the sources of the sediments, and (2) in wave, river, and current action.

The Cambrian system includes all common phases of sedimentary rocks. There are *conglomerates*, presumably laid down near the shores of the time; *sandstones*, the sand of which was deposited in shallow water; *shales*, representing the mud deposits in quiet water; and beds of *limestone* representing, for the most part, the accumulations of shells, etc., where sediments from the land were not abundant.

**Geographic variations.** The distribution of these various sorts of sedimentary rocks shows that various kinds of detrital beds were accumulating in different places at the same time, and at the same place at different times. Not only this, but they were accumulated at very different rates, as the great variations in thickness show.

The fact that the Upper Cambrian in the northern interior of the United States is mostly of sandstone, and that this sandstone is

[1] Chamberlin and Salisbury, Earth History, Vol. II.

widespread, indicates that the water was so shallow that the waves were competent to roll sand long distances. Furthermore, the structure of the beds, with their cross-bedding (Fig. 199), ripple-marks, etc., shows that the whole of the thick series from bottom to top was deposited in shallow water, and therefore on a surface which was depressed gradually, relative to sea-level, as the sand accumulated. The limestone (chiefly dolomite) in the Upper Cambrian of the southern and southeastern interior, points to clear seas, but perhaps not to deep ones. The adjacent lands were perhaps too low to yield abundant sediment. Limestone is also an important part of the Middle and Upper Cambrian of the west, though clastic rocks predominate in the Lower Cambrian. Where the Upper Cambrian is limestone, it is, as a rule, not sharply differentiated from the overlying Ordovician.

### *Outcrops of Cambrian*

The Cambrian formations were once as widespread as the Cambrian seas themselves, but they are not now present over all the area they once covered. The areas where they are exposed are not to be confused with the areas where they actually exist. Cambrian formations are exposed, for example, in Wisconsin, Missouri, and Texas; but the strata of Missouri are doubtless continuous, beneath younger formations, with those of Texas, on the one hand, and with those of Wisconsin, on the other (Fig. 310).

**Position of outcrops.** The map (Fig. 310) showing the areas where the Cambrian system is now exposed reveals several points of significance: (1) Many of the outcrops are in association with outcrops of the Archean and Proterozoic systems (Fig. 295). In places, the exposed Cambrian lies along one border of the exposed parts of these older systems, while in others it completely surrounds them. This distribution is not peculiar to the Cambrian, but is characteristic of most formations as compared with those of greater age. (2) The exposed areas of Cambrian in the Appalachian Mountains occur in parallel or subparallel belts (Fig. 310). This is the result of (*a*) the folding to which the Cambrian and later strata of this region have been subject, and (*b*) the erosion which the folds have suffered. Fig. 314 will help to explain the repetition of outcrops. In this diagram, *A* represents pre-Cambrian strata, *Ꞓ* represents the Cambrian, and *O*, *S*, *D*, and *C*, the Ordovician, Silurian, Devonian, and Carboniferous systems, respectively. After the strata were folded, erosion cut the folds down. A fold involving

Cambrian beds, if truncated below the level of the bottom of these beds at their highest point, exposes two belts of Cambrian strata, one on either side of a pre-Cambrian axis, as represented in the

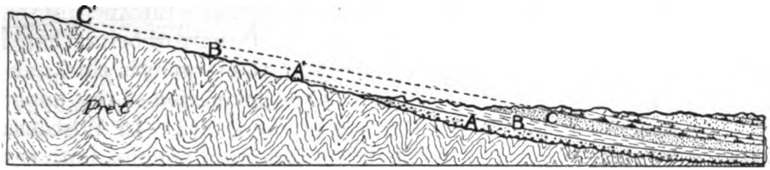



Fig. 312. Diagram illustrating the relation of Cambrian formations, *A*, *B*, and *C*, to older rocks. The diagram suggests that the Cambrian formations have been eroded back from their original margins, *A′*, *B′*, and *C′*.

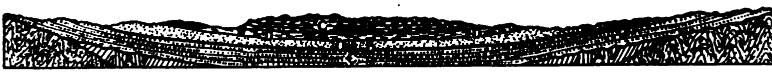


Fig. 313. Diagram illustrating the general relations of Cambrian beds in the interior. The Cambrian, Ꞓ, is represented as appearing at the extremes of the diagram, and as dipping below younger beds between.

left-hand part of the figure. If the truncation is at a level below the top and above the bottom of the Cambrian (right-hand side of

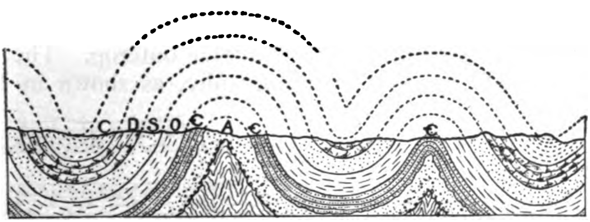



Fig. 314. Diagram showing the positions of outcrops determined by folds.

Fig. 314), the strata of that system are exposed in a single belt along the axis of the fold. (3) In some places, Cambrian outcrops are surrounded by older formations. In such ~~cases the Cambrian~~ outcrops presumably represent remnants which have escaped erosion.

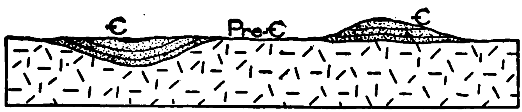



Fig. 315. Figure to illustrate isolated occurrences of Cambrian surrounded by older formations.

They may occupy depressions in the surface of pre-Cambrian formations, or may constitute hills (Fig. 315).

**Width of outcrops.** The widest outcrops of the Cambrian (Fig. 310) are in Wisconsin; yet there the Upper Cambrian only is present, with a thickness of less than 1,000 feet, while in the Appalachian Mountains, where the system has an aggregate thickness of several thousand feet, it appears at the surface in narrow belts; that is, the outcrops are narrow in the east where the system is thick, and wide in the interior where it is thin. The explanation of this apparent anomaly is found in the attitude of the strata. In Wisconsin they are nearly horizontal, while in the mountain regions, both east and west, they are tilted at high angles. Where strata are vertical, the width of their outcrop on a horizontal surface is about the same as the thickness of the beds (€, right-hand side of Fig. 316); where they are nearly horizontal, (€, left-hand side of Fig.) the width of outcrop on a horizontal surface is much greater. It is not to be inferred, however, that horizontal strata always have a wide outcrop. The width of outcrop is also influenced by topography, as shown in Fig. 317.

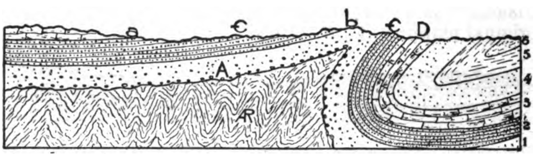



Fig. 316. Diagram illustrating the influence of dip on the width of outcrop. The Cambrian beds, €, to the left have a much wider outcrop than the Cambrian beds to the right, though the thickness is the same.

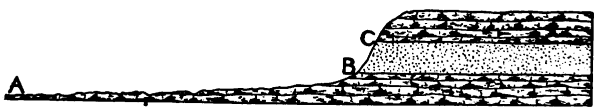



Fig. 317. Diagram illustrating the effect of topography on width of outcrop.

Here the horizontal stratum between *B* and *C* has about the same thickness as € of Fig. 316, but its outcrop is narrow. In general, the width of outcrop, so far as determined by topography, depends on the angle between the bedding-planes and the surface where the formation outcrops. The width of the outcrop decreases as this angle increases.

## *Changes in Sediments Since Deposition*

The sediments of the Cambrian system have undergone change since their deposition. In most regions they have been compacted and cemented into solid rock. Over great areas in the interior

(Figs. 312 and 313) the strata still remain nearly horizontal, while in some other regions they have been tilted, folded, and faulted

Fig. 318. A section in the Menominee region of northern Michigan, showing the Potsdam sandstone, *€s*, in unconformity with older formations. (Van Hise, U. S. Geol. Surv.)

Fig. 319. Section showing relations of the Cambrian in the Appalachian Mountains. The strata are folded and faulted. *€*, Cambrian; *O*, Ordovician; *S*, Silurian. Length, 13 miles. (Hayes, Cleveland [Tenn.] folio, U. S. Geol. Surv. Ordovician and Silurian not separated in the original.)

(Fig. 319). Where close folding has taken place, the rocks have been more or less metamorphosed. In extreme cases the sandstones

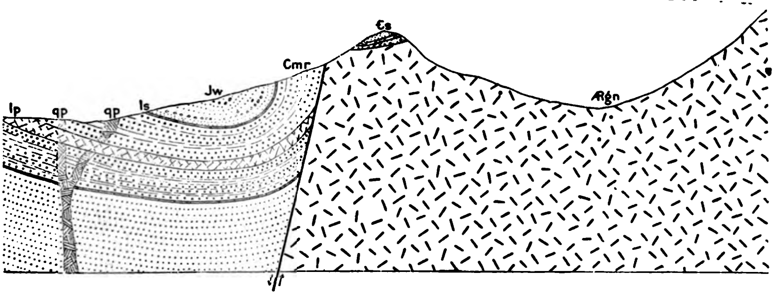



Fig. 320. Section showing the relations of Cambrian and other formations at a point north of Leadville, Colorado. *Æ gn*, Archean; *€s*, Cambrian; *Cmr*, Carboniferous; *Jw*, Jurassic; *lp* and *qp*, igneous rocks. (Emmons, U. S. Geol. Surv.)

have been converted into quartz schists, the shales into slates and schists, and the limestones into marble.

### *Close of the Period*

No physical changes of great importance seem to have marked the close of the Cambrian period in America. Nowhere in our continent, so far as now known, were mountains made at this time, and nowhere were great areas of sea-bottom converted into land, though local unconformities between this system and the next record local changes in the sites of deposition.

## *The Cambrian in Other Continents*

**Europe.**[1] In Europe, as in North America, widespread deformation before the beginning of the Cambrian converted large areas of the present continent into land, and there is evidence that these lands, like those of America, were subjected to protracted erosion before the deposition of the Cambrian system.

The Cambrian system of Europe, like that of America, is largely clastic. Ripple-marks, cross-bedding, and sun-cracks are common, showing that a large part of the Cambrian sediments were laid down in shallow water, or on land.

In Wales (Cambria), the country from which the system got its name, and in Brittany, the system is very thick. In Scandinavia and western Russia, on the other hand, it is thin, locally no more than 400 feet. These differences probably mean that sediments were being deposited in some places many times as rapidly as in others. The Middle Cambrian of Europe is more ~~widespread than the Lo~~wer or Upper, showing that changes in the relation of sea and land were in progress during the Cambrian period, shifting the areas of erosion and sedimentation.

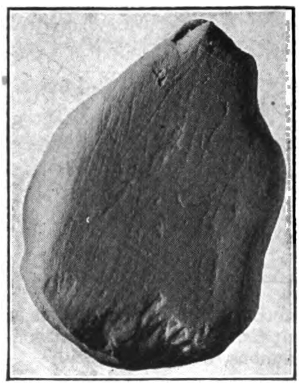


Fig. 321. Glaciated stone from the glacial beds at the base of the Cambrian in China. (Willis, Carnegie Institution.)

The Cambrian of western Europe has been much folded, but in central and eastern Europe, the strata are essentially horizontal. Beds of clay which are still plastic, and beds of sand which are still uncemented, are known in the undeformed part of the system. Geographic changes of great importance seem not to have marked the close of the Cambrian, in Europe.

**Other countries.** Cambrian rocks occur in various parts of Siberia, China, India, ~~Australia,~~ and Tasmania, and in the northwestern part of Argentina, but their distribution outside of North America and Europe is but poorly known.

**Glacial formations.** (1) In northern *Norway*, Lat. 70° 8′ N.,

[1] The best summary, in English, of the Cambrian of Europe, is found in Geikie's Textbook of Geology, 4th ed., Vol. II.

there is a bowlder-bearing formation (the *Gaisa* beds) resting on a glaciated surface of crystalline rock. The Gaisa beds have been thought to belong to the oldest part of the Cambrian system, or to antedate it. (2) Recent exploration in *China*[1] has made known a thick formation (170 feet) of bowlder-bearing rock of glacial origin, containing many striated bowlders of diverse sorts of rock (Fig. 321) on the Yangtse River, in latitude 30°. This formation lies at the base of the Paleozoic, beneath the beds that carry

Fig. 322. A glaciated bowlder from the Cambrian till of Petersburg, South Australia. (Howchin.)

Cambrian trilobites. Glacial formations of early Cambrian age have been found in *Australia*, and perhaps in *South Africa*.[2]

The profound climatic significance of these glacial formations is obvious. The testimony of Cambrian fossils, on the other hand, implies nearly uniform climatic conditions throughout all regions where fossils have been found, and the wide spread of the sea during the later part of the period would seem to point to oceanic, rather than continental, climates at that time.

### *Duration of Cambrian Period*

There is no reliable estimate of the duration of the Cambrian period. The destruction and removal to the sea of such large volumes of rock as are represented by the sediments of the system

[1] Willis, Researches in China, Vol. II.

[2] David, Report of International Geological Congress at Mexico, 1907; and Howchin Quar. Jour. Geol. Soc., Vol. LXIV, p. 234, 1908, and Jour. of Geol., Vol. XX, pp. 193–8.

required a very long period of time; but since there is no standard rate at which any sort of sediment accumulates, this long period cannot be reduced to years. It has been estimated that limestone sometimes forms at some such rate as one foot per century. In some parts of the West there are 6,000 feet of limestone, besides thick bodies of fragmental rock. At the above rate of accumulation, 6,000 feet of limestone would call for a period of 600,000 years, and if time be allowed for the other formations of the same region, this period would be lengthened greatly. It should be remembered, however, that while one foot per century is a rate at which limestone may accumulate, it does not follow that it is the rate at which Cambrian limestone was formed.

Many estimates of geological time, based on various data, have been attempted.[1] These estimates, so far as applied to the Cambrian, generally assign to that period a duration of 1,000,000 to 3,000,000 years. It should be distinctly borne in mind, however, that the chief value of these figures is to give emphasis to the fact that the period was one of great duration. For aught that is now known, the largest of these figures might be multiplied by 2 or even by some larger number.

### LIFE OF THE CAMBRIAN

Perhaps no single event in the history of the earth possesses greater interest than the first appearance of life; but the date of its beginning is not known. There is good evidence that life existed before the close of the Archeozoic era, and under the accretion hypothesis, it is not improbable that its beginning antedated, by a long period, the oldest accessible Archean formations. If so, it is quite beyond hope that the earliest forms of life will ever be known from fossils. The known fossils from the Proterozoic rocks give but a very inadequate conception of life before the Cambrian. But in the Cambrian system there is, for the first time, a reasonably adequate record of animal life.

**Animal fossils.** Every great division of the animal kingdom, except the vertebrate, was representated in Cambrian times, and though no vertebrate remains have yet been found, it would be rash to assume that no vertebrates lived. All the known fossils appear to be of marine species. Of land animals there are no traces, but this does not prove that they did not exist.

[1] For a general discussion of this topic, see Williams' *Geological Biology*, Chap. II.

Trilobites were easily the most distinguished forms of Cambrian life. They were not only the highest in organization, but the most characteristic of the period. Their successive genera best distinguish its successive stages, and their distribution is a chief means of correlating the formations of different regions. Figs. 311 and 323 show their three longitudinal lobes, whence their name. Trilobites were kin to the modern crab and crayfish, representatives of the great group Arthropoda (p. 686). They have long been extinct, but the modern horse-shoe crab has some likeness to them.

Trilobites were well advanced in the scale of development, possessing nearly all the anatomical systems and physiological functions of modern crustaceans. Perhaps their compound eyes are the best index of their development. In this and succeeding periods, the number of eyelets in trilobites' eyes ranged from a score to several thousands. Some of them, however, had no eyes, while others possessed abortive rudiments, implying that their ancestors had possessed them. The acquisition and abortion of so important an organ seem to indicate change in the conditions of life. This may mean no more than migration to deep dark waters, or the habit of burrowing in the mud, where eyes were useless. The eyes of some were raised slightly on crescentic lobes, with the convex face outwards (*a* and *c*, Fig. 323). In later epochs, these cres-

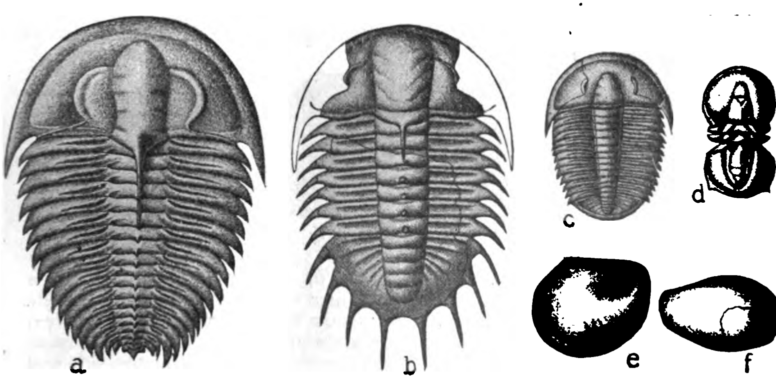



Fig. 323. Cambrian Crustacea: *a*, *Holmia* (*Olenellus*) *bröggeri* Walcott, a characteristic trilobite of the Lower Cambrian; *b*, *Olenoides curticei* Walcott, a Middle Cambrian trilobite; *c*, *Ptychoparia kingi* Meek, a Middle Cambrian trilobite; *d*, *Agnostus interstrictus* White, a Middle Cambrian trilobite; *e*, *Aristozoœ rotundata* Walcott, a Cambrian phyllocarid; *f*, *Leperditia dermatoides* Walcott, a Cambrian ostracode.

cents became more and more curved, extending the sweep of vision fore and aft, to the animal's obvious advantage.

The upper surface of the body was ornamented variously, and the ornamentation varied as time went on, increasing, in general, until after the climax of the trilobites had been passed. Trilobites possessed a row of slender articulated legs on either side, and delicate filaments which served the function of respiratory organs. The nature of the legs indicates that trilobites both walked and swam. They possessed antennæ which doubtless served as organs of touch, and they moulted the shell at successive stages of growth, like modern crabs. Omitting further details, it is to be observed that, at this early day, a highly complex, well-differentiated organization had been acquired, possessing nearly all the organs and functions of arthropods of the present day.

*Brachiopods* (*molluscoidea*, p. 686 and Fig. 324) were second in geological importance to trilobites; but unlike trilobites, brachiopods still live. They are conspicuous representatives of stability and persistence. Though the species and most of the genera have

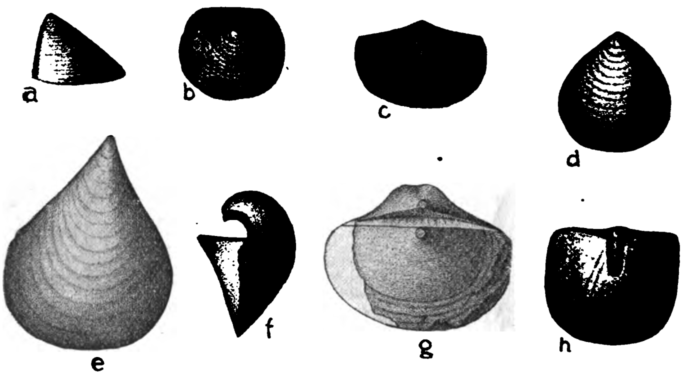



Fig. 324. CAMBRIAN BRACHIOPODS: *a* and *b*, ***Acrotreta gemma*** Billings, a brachiopod ranging from the Lower to the Upper Cambrian, summit and side views of the ventral valve; *c*, ***Billingsella transversa*** Walcott, a pedicle or ventral valve of a hinged brachiopod of the Lower Cambrian; *d* and *e*, ***Lingulepis pinniformis*** Owen, views of the two valves; *f* and *g*, ***Kutorgina cingulata*** Billings, side and dorsal or brachial views, a Lower Cambrian species; *h*, ***Billingsella coloradoensis*** (Shum.), an Upper Cambrian species.

changed, the class as a whole has been but slightly modified since the Cambrian period. The brachiopod shell is bivalve. The two valves are unlike, but each is bilaterally symmetrical (Fig. 324).

*Mollusks* (p. 686) were well represented, *Cephalopods* (chambered shells), the highest class of mollusks and are found in the uppermost beds of the Cambrian. As they were even then highly developed, there is little doubt that the class had passed through a long history before the end of the period. *Pelecypods* (bivalves, oysters, clams, etc., *b*, Fig. 325) lived throughout the period, though their

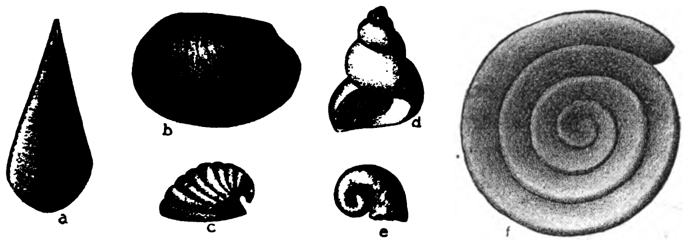



Fig. 325. CAMBRIAN MOLLUSKS: *a*, *Hyolithes americanus* Billings, a Lower Cambrian pteropod; *b*, *Fordilla troyensis* Barrande, a Lower Cambrian pelecypod; *c*, *Stenotheca rugosa* Hall, a capulid gastropod of the Lower Cambrian; *d*, *Trocus saratogensis* Walcott, a gastropod with well-developed spire; *e*, *Platyceras primævum* Billings, a Lower Cambrian gastropod; *f*, *Ophileta primordalis* Winchell, an Upper Cambrian gastropod.

fossils are not abundant. Like brachiopods, pelecypods are bivalves, but unlike the brachiopods, the valves are not bilaterally symmetrical. *Gastropods* (univalves, *c*, *d*, *e*, Fig. 325) are rather

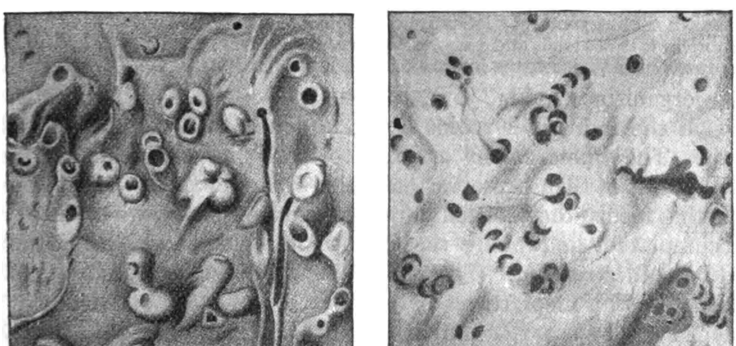



Fig. 326. CAMBRIAN VERMES: borings and trails. *a*, a surface of sandstone showing annelid borings, with mounds of sand heaped about their mouths and with trails leading away from some of them.

plentiful throughout the system. The early forms are chiefly of the low conical type, while more amply coiled and spiral forms became common later. Some of them resemble modern gastropods closely.

*Sea worms* (*Vermes*, p. 686) left evidence of their abundance by borings, tracks, etc. (Fig. 326). A few *cystoids*, the forerunners of the beautiful crinoids (stone lilies), represented the echinoderms.

*Cœlenterates* were represented by graptolites, medusæ and polyps (corals). The eccentric freaks of fossilization are nowhere better illustrated than here. Relics of *graptolites*, among the most delicate of animal forms, and of *medusæ* (jelly-fish), among the softest of animals, were preserved, while some stronger types left scant record of themselves. *Graptolites*, now extinct, were slender, plume-

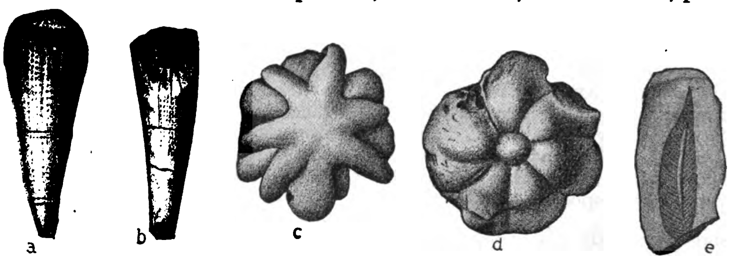



Fig. 327. Cambrian Cœlenterata: supposed corals, medusæ, and graptolites. *a* and *b*, *Archæocyathus rensselæricus* Ford, a problematic fossil referred by some paleontologists to sponges, and by others to corals; *c* and *d*, *Brooksella alternata* Walcott, supposed casts of the gastric cavities of medusæ; *c*, a supposed exumbrella in which the interumbrella lobes are a prominent feature; *d*, a view of a supposed umbrella with six lobes and a depression over the central stomach; *e*, *Phyllograptus* (?) *cambrensis* Walcott, the hydrosoma of a graptolite.

like organisms (*e*, Fig. 327), consisting of a series of hard cells, in which the individual zoöids lived, attached to a common slender axis. The whole colony appears to have floated free in the sea. The secret of their preservation probably lies in the fact that, being floating forms, they settled in quiet waters off-shore, where fine silts accumulated, and where the conditions were favorable for burial without destruction. The most singular case of fossilization is the preservation of traces of *jelly-fish*, or at least of what are so identified (Fig. 327, *c* and *d*) in the Lower Cambrian. Obscure fossils of *corals* are found (Fig. 327, *a* and *b*), the forms of which resemble sponges so much that they long were regarded as such. Corals seem to have been more abundant in some other parts of the world than in North America.

*Sponges* lived throughout the period. It is probable that many *protozoans* existed, but only a few forms have been identified.

**Implied life.** The existence of so much animal life implies much vegetable life to supply the necessary food. Furthermore, various characteristics of the fossils suggest the presence of animals not known from fossils. A large percentage of the known Cambrian animals were provided with shells, tests, plates, or other forms of hard coverings. In the main, these appear to have been protective devices, and imply enemies or rivals against which protection was needed. Perhaps the most significant feature of the protective devices is that they are of the same types as those possessed by similar animals of later times. If there had been a radical change in the character of their enemies or rivals, we might expect some notable change in the defensive devices. It is a natural inference, therefore, that the conflicts of life in the Cambrian seas were similar to those of the present. The inference may be pushed further, and the deduction drawn that the conflicts which led to the evolution of the defensive devices were much like those throughout the period of their retention.

**Stage of evolution represented.** What stage of advancement in the development of life had been attained by the beginning of the Cambrian period? Do the fossils of the system indicate that the life of the period was primitive, or do they imply that it had advanced far beyond primitive forms? For comparison it may be assumed that the first forms of life were as simple as the simplest existing forms. If the plants and animals that consist of a single cell are taken to represent primitive forms, how far had the Cambrian life advanced beyond them?

In the early stages of their development, animals pass through a succession of changes in which their structure resembles that which their ancestors had in their maturity; in other words, the individual history of any animal is an epitome of the history of its ancestors. Now the Cambrian trilobites are known to have passed through a series of remarkable changes after the individuals had developed far enough to be fossilized, and it is inferred they passed through other stages previously. There is, therefore, specific ground for believing that they had had a long line of ancestors.

On the anatomical and physiological side, it is clear that nearly or quite all the fundamental organs had been developed. There were skeletal systems of several forms, muscular systems, nervous

systems of high development, as implied by eyes and other sense-organs, devices for capturing and ingesting food, organs of digestion, secretion, excretion, and respiration. The Cambrian animals had acquired the various habits of life possessed by existing animals of their kind, as well as the various modes of preserving their lives.

The question may be approached in another way. The studies of recent decades have convinced investigators that later forms of life were derived from earlier ones by processes of evolution. The exact methods of evolution are not altogether understood, but the fact of evolution is not now regarded as an open question. As the various forms developed and diverged from a common ancestral stock, many of the intermediate forms disappeared, and the forms which persisted became widely separated. By continued divergence, with the loss of intermediate types, a discontinuous series of forms was developed, and those which lived on became more and more unlike. The process was not unlike the evolution of a tree-top, in which the dying out of most of the interior branches leaves a few great limbs which bear the more numerous and more recent branches, while these in turn bear the uppermost and outermost twigs which represent the living phase. In some such way, it is thought that the existing divergence of organisms into kingdoms, branches, classes, orders, families, genera, species, and varieties came to be established.

If it is assumed that the whole system of living things was derived from a common primitive form, or from a few primitive forms, a comparison of the primitive state with the degree to which life had advanced in the Cambrian period will give some impression of the amount of pre-Cambrian evolution. If to this be added a comparison between the Cambrian life and that of today, an estimate of the relative amount of evolution before and since the Cambrian may be made.

It is to be noted that not only were all the animal sub-kingdoms, save perhaps the vertebrate, present, but that, in many of them, the species had come to have nearly the aspect of living forms. *The initiation and divergence of the structures and types that preceded the Cambrian stage mean much more in the way of evolution than all the evolution of later times.* These considerations lead to the conclusion that life must have been in existence a very long time prior to the Cambrian period.

**The succession of faunas.** Under the doctrine of evolution, it

is presumed that the life of every past stage has grown out of that which immediately preceded it, and that it has merged into that which immediately followed it. It is usually assumed that if no exceptional influences came in, there was a continuous series of slow changes without sharp lines of demarkation. If this conception were realized in fact, it would be less appropriate to speak of a succession of faunas than of one continuous ever-changing fauna. It is not yet demonstrated, however, that evolution proceeded solely by very slight changes coming in from generation to generation. It may have proceeded by distinct and abrupt changes;[1] or at any rate new species may have arisen abruptly, so far as now known. Irrespective of any other specific hypothesis, it is to be noted that the geological record, as now known, does not show complete gradations from one species to another. In some cases there is something of a graded series, but the steps of the gradation are not sufficiently close and definite to decide between evolution by an infinite number of small changes, and a smaller number of greater changes.

If we turn from species to faunas, a more general point of view must be taken. Observation shows that in some cases one fauna grades into the succeeding one, while in other cases the change appears to be abrupt. If the progress of life the world over could be studied as a unit, it would probably appear that there was a nearly perfect gradation of the life of one stage into that of the next. This gradation probably was more rapid at some times than at others, and it is quite certain that some forms changed more rapidly than others. But when we limit our study to the succession of faunas on any one continent, or to any one province, it is evident that the progress of evolution in the region studied was interrupted by physical changes which affected the depth, temperature, or clarity of the water, and the nature of the bottom, and that these changes brought about variations in the character and distribution of life. There seem to have been rather definite times of notable change, between which faunas changed but slowly. Where the faunal change in a conformable series is abrupt, and there is no evidence of a gap in the record, the explanation is usually sought in the immigration of a new fauna from some other region.

In the study of faunal progress, therefore, there is occasion

[1] DeVries. Die Mutationstheorie, 1903. See also Bateson's Material for the Study of Variation, 1894; W. B. Scott, On Variations and Mutations, Am. Jour. Sci., 1894. p. 355; and discussions of Mendel's theory.

to recognize (1) rather abrupt changes brought about by overwhelming invasions; (2) less abrupt changes brought about by the more gradual ingress of outside species, and the gradual commingling of immigrants with resident species; (3) very gradual changes due to the slow evolution of resident species when not much affected by immigration or by physical changes; and (4) rapid evolution due to profound changes in the physical conditions or to other agencies less well understood.

**The abrupt appearance of the Cambrian fauna.** The apparent suddenness of the appearance of the Cambrian fauna is unexplained. In a general way, it may be said that older formations have been metamorphosed, and that this destroyed most of their fossils; but this suggestion is not altogether adequate, for some of the older formations are not greatly changed, and some younger metamorphic rocks carry fossils. It is also true that some younger formations which seem well suited to receiving and retaining organic impressions are without them. Geologists are inclined to refer the scantiness of pre-Cambrian fossils, and hence the *apparent* abruptness of the introduction of the Cambrian fauna, to unfavorable conditions for fossilization in pre-Cambrian time, combined with subsequent changes in the rock. This makes the abruptness a matter of record, rather than of fact.

*Map work.* Suggestions for work with geologic folios are found in *Laboratory Exercises in Structural and Historical Geology*, SALISBURY AND TROWBRIDGE, Exercise VIII.

# CHAPTER XVI

## THE ORDOVICIAN (LOWER SILURIAN) PERIOD [1]

### FORMATIONS AND PHYSICAL HISTORY

The general conformity [2] between the Cambrian and Ordovician systems shows that no great change took place in the relations of land and water in North America at the close of the Cambrian period. At the opening of the Ordovician, therefore, an epicontinental sea stood over much of the continent.

### *Sedimentation During the Ordovician Period*

While the principles of sedimentation during this period were the same as during the Cambrian, the conditions, so far as our continent is concerned, were somewhat different, chiefly because the smaller areas of land yielded less sediment. During much of the period the deposition of land-derived detritus was confined to littoral tracts. Since the land areas were of various sizes, of various sorts of rock, and presumably of various heights, conditions existed for the deposition of all sorts of clastic sediments about their borders, and for their deposition at very different rates. Sedimentation was doubtless more rapid near the larger and higher lands than about the smaller and lower ones, and more rapid on that side of any land towards which the larger part of its drainage flowed. Where clastic sediments failed, the shells and other secretions of marine animals and plants were accumulating, making limestone.

The known formations of the Ordovician period are in keeping with these general principles. Adjacent to the broad, shallow

[1] Recently it has been proposed to recognize a system of rocks, the *Ozarkian*, between the Cambrian and the Ordovician, the Ozarkian would include the lower part of the Ordovician (Beekmantown formation and its equivalents), and the upper formations of certain regions commonly referred to the Cambrian. Ulrich, Bull. Geol. Soc. Am., Vol. XXII.

[2] There are local unconformities between these systems, as in some parts of New York, and the evidence is increasing that they are more wide-spread than formerly was supposed.

arm of the ocean which covered the larger part of the Mississippi basin (Fig. 310) there appear to have been no sources of abundant sediments during most of the period. Along the western base of Appalachia, clastic materials were being deposited. Alternating beds of coarse and fine sediment indicate either (1) that the adjoining land was higher at some times than at others, or (2) that the climatic conditions or (3) the vegetal covering changed, or (4) that waves and currents varied in their effectiveness.

Conditions for the formation of limestone prevailed widely in the epicontinental sea. Plants and animals secreting calcium carbonate may have been no more abundant far from land than near it, but away from shore their shells, etc., were more abundant *relative to the sediments derived from the land.*

The development of the Ordovician system meant the destruction of an equivalent body of older rock. The material which entered into the new system came from all preceding formations so situated as to be exposed to erosion. Even the limestones of the system had their ultimate source in older formations, for the mineral matter extracted from the sea to make the shells had been dissolved from older formations during their decay, and brought to the sea in solution, largely by the same streams which carried the clastic sediments.

**Sections of the Ordovician.** The Ordovician system of North America was first studied carefully in New York, and the section of that State is, in some measure, the standard to which others are referred. In New York the system is divided as follows:

| | | |
|---|---|---|
| Ordovician | Upper Ordovician (or Cincinnatian) | Richmond beds[1] (in Ohio and Indiana) |
| | | Lorraine beds |
| | | Utica shales |
| | Middle Ordovician (or Mohawkian) | Trenton limestone |
| | | Black River limestone |
| | | Lowville limestone |
| | Lower Ordovician (or Canadian) | Chazy limestone |
| | | Beekmantown limestone (Calciferous) |

The classification of New York is not applicable in detail in other parts of the continent. In Wisconsin, Iowa, and Minnesota, for example, the formations commonly recognized, numbered in the

[1] Question has been raised as to the propriety of including the Richmond beds in the Ordovician. Hartnagle, N. Y. State Mus. Bull. 107, 1907. In Illinois, beds of Richmond age are unconformable on the older Ordovician. Weller, Jour. of Geol., Vol. XV, p. 519; and Savage, Am. Jour. Geol., Vol. 125, p. 431, 1908.

order of age, are shown below, but it cannot be affirmed that any one of them is the exact equivalent of any one in New York.

| | | |
|---|---|---|
| Upper Ordovician | | 5. Hudson River[1] (Maquoketa) shale |
| Middle Ordovician | { | 4. Galena limestone |
| | | 3. Trenton limestone |
| Lower Ordovician | { | 2. St. Peter sandstone |
| | | 1. Lower Magnesian limestone |

In the mountains of Tennessee, a series of limestone or dolomite beds (Knox, Chickamauga, etc.), is followed by a series of clastic beds (Sevier shale, Bays sandstone, etc.).[2] The exact relations of these formations to those of New York and to those of the upper Mississippi basin are undetermined. The section of Tennessee does not correspond in detail with that of other parts of the Appalachian belt.

In the Great Plains, the Ordovician system appears at the surface but rarely, though it probably underlies the younger formations.

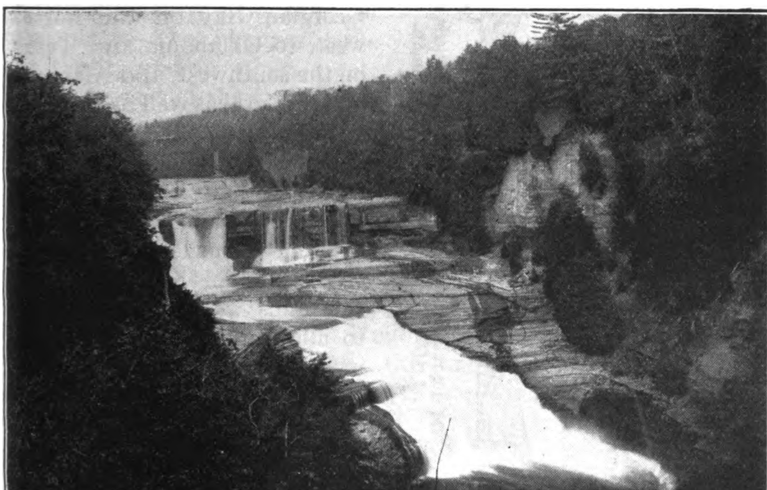


Fig. 328. Trenton Falls, Trenton, N. Y. The locality whence the Trenton formation derived its name. (Darton, U. S. Geol. Surv.)

[1] It is now held by some that a portion, if not all, of the Hudson River (Maquoketa) shale of the Mississippi basin is the equivalent of the Richmond beds farther east.

[2] The subdivisions mentioned here are those of the Maynardsville, Tenn., folio, U. S. Geol. Surv.

West of the Great Plains, the system is present generally, and the sections are somewhat simpler than in the interior or the east, limestone being a conspicuous part of the system here.

**General conditions in the eastern part of the continent.** At no previous epoch was there anything like such widespread deposition of limestone within the limits of our continent, as in mid-Ordovician time, when limestone was forming from New England on the east, to Georgian Bay on the northwest, to Oklahoma and Texas on the southwest, and Alabama on the south, as well as in much of the west. It is perhaps equally worthy of note that in the later part of the period, mud (now shale) was deposited over an almost equally extensive area. This may mean that the lands were so elevated as to allow the streams to carry more sediment to the sea, or that conditions favored the transportation of mud farther from shore than formerly, or both. All the Ordovician formations of the interior and the east bear within themselves evidence of shallow water origin.

**Igneous rocks** of Ordovician age attain little importance in North America. Their general

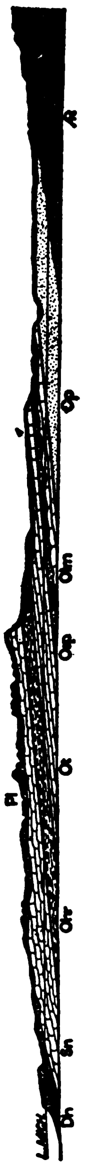


Fig. 329. Section of the formations in southern Wisconsin, showing the position of the beds and the relations of the several systems to one another. The section extends from the Archean area, in the north-central part of the state, to Lake Michigan, in the vicinity of Milwaukee. *Æ*, Archean; *Ꞓp*, Potsdam sandstone (Cambrian); *Olm*, Lower Magnesian Limestone; *Osp*, St. Peter sandstone; *Ot*, Trenton and Galena limestone; *Ohr*, Hudson River shales. The last four formations are Ordovician, unless, as recently suggested, p. 368, the last be Silurian. *Sn*, Niagara limestone (Silurian); *Dh*, Hamilton limestone (Devonian,) and *Pl*, glacial drift (Pleistocene). Length of section, about 135 miles.

Fig. 330. Section showing the relations of Ordovician and other beds at a point in West Virginia. *ꞒO*=Cambro-Ordovician; *O*=Ordovician; *S*=Silurian; *SD*=Siluro-Devonian; *D*=Devonian. Length of section, 18 miles. (Darton, Monterey (W. Va.) folio, U. S. Geol. Surv.)

absence is in harmony with the quiet which characterized the period.

*General Conditions and Relations of the Ordovician System*

**Position of beds.** As originally deposited, the Ordivician beds probably dipped away from the lands of the period. Over great areas in the interior, this original and simple plan of stratigraphy has been but little modified (Fig. 329). In other regions, deformation of the strata has completely changed their original positions. Thus in the Appalachian Mountains (Fig. 330) and in some parts of Arkansas (Fig. 331), Oklahoma, and various mountains of the west, the strata are folded and in some places faulted.

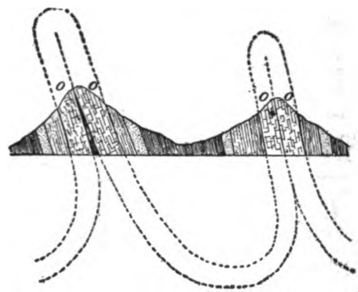


Fig. 331. Section showing the position and relations of the Ordovician beds in the mountains of Arkansas. Length of section, about 1⅓ miles. (Penrose, Ark. Geol. Surv.)

*Metamorphism.* The sediments have undergone more or less alteration since their deposition. In some places the changes have been slight, and in others great. The larger part of the Ordovician sands have been changed to sandstone, the larger part of the muds to shale, and most of the limestone is still essentially non-metamorphic. But where dynamic action has been great, and where the original position of the strata has been changed greatly, the changes in the rock have been greater.[1] Thus in the Taconic Mountains (southeastern New York and southwestern New England), the limestone has been changed to marble, the sandstone and quartzite to quartz schist, and the shale to slate and schist.

**Thickness.** The rocks of all systems vary greatly in thickness, and the Ordovician system is no exception. In the Appalachian Mountains it is thousands of feet thick, while in the interior it is only hundreds. In Wisconsin and Iowa, the aggregate thickness is rarely more than 800 or 900 feet.

**Outcrops.** In the interior, where the system is relatively thin,

[1] See, for example, the New York City, Holyoke (Mass.-Conn.), and Hawley (Mass.) folios, U. S. Geol. Surv. Compare with folios of the Appalachian Mountains, the interior, and the western part of the United States.

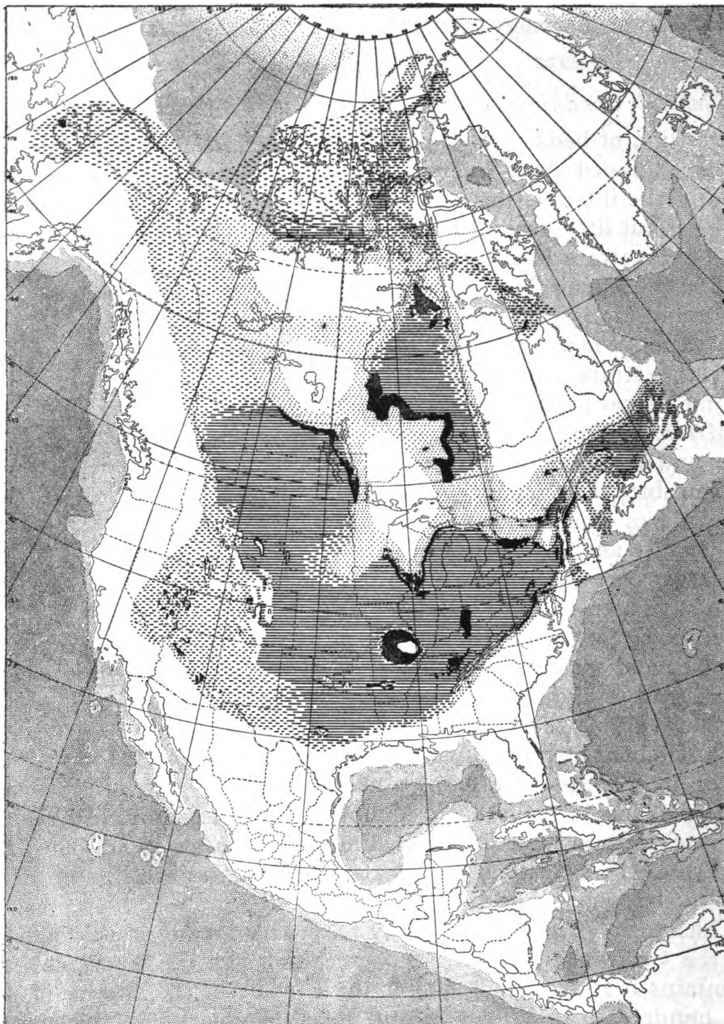


Fig. 332. Map showing the general condition of the North American continent in Mid-Ordovician (Trenton) time. The black portions represent areas where the Middle Ordovician beds appear at the surface. These areas so nearly correspond with the areas where the Ordovician system as a whole appears at the surface, that no serious error is involved if the black areas be interpreted as Ordovician. The various conventions of the map are the same as in Fig. 310, p. 347.

it appears at the surface in relatively wide belts or areas (Fig. 332), while in the eastern mountains, where it is thick, it appears at the surface in a succession of narrow and parallel belts (p. 372). The outcrops are largely adjacent to older rock.

### *Close of the Ordovician Period*

The close of the period was marked by geographic changes of more importance than those at its beginning. The greatest change was the withdrawal of the epicontinental waters from a large part of North America, converting extensive stretches of shallow-sea bottom into land. The cause of this change may have been the sinking of the ocean bottoms and the drawing off of the epicontinental waters. The altitude of the new land must have been slight or its exposure brief, for it suffered little erosion before much of it was again submerged and covered by sediments of later age. It is indeed the widespread absence of the lower part of the Silurian system, apparent or real (p. 388), rather than a pronounced stratigraphic unconformity between it and the Ordovician, which indicates the extensive emergence of land in the interior at the close of the Ordovician period.

Folding movements were limited. The most considerable were in the Taconic Mountains, where both the Cambrian and Ordovician systems were thick. The date of the folding is known, because Silurian formations overlie the Upper Ordovician unconformably in this region. It is not to be inferred that all the mountain-making movements which have affected western New England occurred at this time. There had been folding earlier, in pre-Cambrian times, and there were movements later as will be noted. The principal deformation of the strata in the Appalachians and in Arkansas came much later.

Between folding and the more gentle movements already noted there are all gradations. The "Cincinnati arch" is an example. This arch is a very low anticline with a general north-south course, extending through Cincinnati. The beginning of this arch may have been as early as mid-Ordovician. Another similar arch [1] may have come into existence at about the same time in Arkansas and Oklahoma.

The crustal movements referred to above have been mentioned

[1] Branner, Am. Jour. Sci., Vol. IV, 1897, p. 357. This very suggestive article has bearings on many questions besides the Ouachita Uplift.

as occurring at the close of the Ordovician. It would perhaps be more accurate to say that their beginning marks the beginning of the transition from the Ordovician period to the Silurian. The duration of the interval of transition was probably long.

*Economic Products*

In Ohio and eastern Indiana the Trenton formation yields much gas and oil.[1] Both are commonly held to be products of the decay or distillation of organic matter included in the sediments when they were deposited. The oil is most abundant under low anticlines, where it occurs in the pores and openings of the rock, somewhat as ground-water does.

The Galena and Trenton formations in Wisconsin [2] and in the adjacent parts of Iowa and Illinois contain ores of lead and zinc, mainly in the form of sulphides and carbonates. Lead ores are also found in the Ordovician (or Cambro-Ordovician) formations of southeastern Missouri,[3] and lead and zinc ores in the south-central part of the same state. In all these regions the ores occur (1) in cavities formed by solution, (2) as replacements of limestone, or (3) in crevices. In these positions, the ore was concentrated by ground-water. The metallic substances were doubtless derived from the limestone itself, which, at the time of its deposition, is thought to have contained trifling amounts of lead and zinc, perhaps extracted from sea-water by organisms.

The Ordovician limestones of central Tennessee [4] locally yield

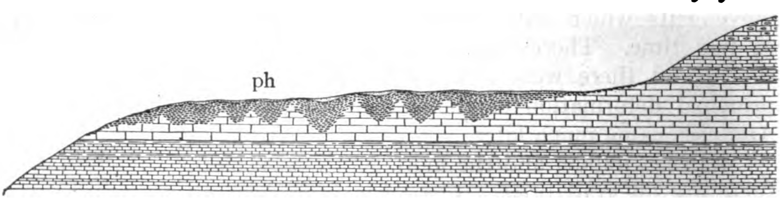



Fig. 333. Shows modes of occurrence of the phosphates (the shaded surface parts of the limestone, ph) in central Tennessee. (Hayes and Ulrich, Columbia (Tenn.) folio, U. S. Geol. Surv.)

[1] Orton, 8th Ann. Rept., U. S. Geol. Surv.; Phinney, 11th Ann. Rept.; also the reports of the State Geol. Surv. of Ohio and Indiana.

[2] Chamberlin, Geol. of Wis., Vol. IV, 1879, pp. 365–568; Calvin and Bain, Iowa Geol. Surv., Vol. VI, and Grant, Bull. XIV, Wis. Geol. Surv., 1906.

[3] Winslow, Missouri Geol. Surv., Vols. VI and VII, and Buckley, Vol. IX.

[4] Hayes. Columbia (Tenn.) folio, U. S. Geol. Surv.

calcium phosphate, valuable as a fertilizer. The workable deposits have resulted from the leaching out of the calcium carbonate from the phosphatic limestone, leaving the less soluble calcium phosphate concentrated at the surface (Fig. 333). The manganese ore of Arkansas had a similar origin.

### *Foreign Ordovician*

The Ordovician formations appear at the surface in various parts of Europe, and they exist beneath younger formations over considerable areas where not seen. Fig. 334 represents the general

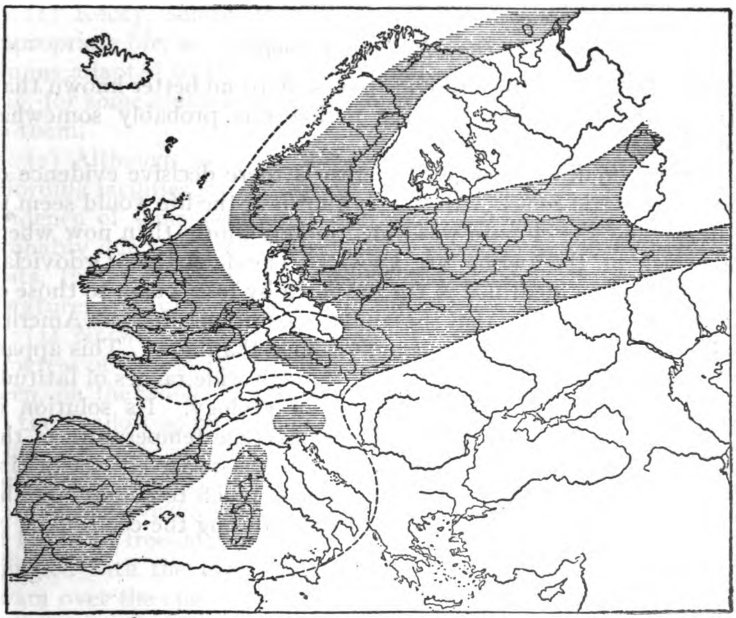


Fig. 334. Diagram showing the relations of land and water in western Europe in the Ordovician period. The shaded parts represent areas of marine sedimentation. (After DeLapparent.)

geographic relations of land and water in Europe during this period. The submerged area represents in a general way the area where the Ordovician formations are present. In contrast with North America, the Ordovician formations of Europe are largely fragmental. In the British Isles Ordovician strata are very thick (something like

24,000 feet maximum).[1] Locally (Wales), nearly half the system is of igneous rock, including sheets of lava and beds of pyroclastic material. This is one of the most extensive, as well as one of the most ancient, volcanic tracts of Europe. From north England and Wales the system thins in all directions.

The Ordovician of Europe is generally conformable on the Cambrian, but over considerable areas it is unconformable beneath the Silurian.

In other continents the Ordovician strata have not, as a rule, been separated from the overlying Silurian, but they are known in South America, Australia and China.

### *Duration and Climate*

The duration of the Ordovician is perhaps no better known than that of the Cambrian, but the period was probably somewhat shorter than its predecessor.

Neither in Europe nor in America is there decisive evidence of distinct climatic zones. All that is known of the life would seem to indicate that the climate was much more uniform than now where the strata of the period are known. The fact that Ordovician rocks have been identified in the far north by fossils akin to those of low latitudes, indicates that the climatic conditions of North America and Europe must have been less diversified than now. This apparent lack of diversity of temperature through wide ranges of latitude is one of the unexplained problems of geology. Its solution is possibly to be found in a much higher average temperature of the ocean.[2] If the body of the ocean-water was relatively warm (instead of cold as now), it would have done much to counteract the effect of slight insolation in high latitudes during the cooler part of the year.

## LIFE

From Cambrian to Ordovician, there was no pronounced break in the succession of life. The time from the beginning of the first to the close of the second of these periods appears to have been one long eon of progressive development and expansion of life. The fossil record of the Ordovician is fuller than that of the Cambrian. This is due partly to an increase in fossilizable forms, partly

[1] This measurement is doubtless subject to the strictures set forth on p. 355.
[2] Chamberlin and Salisbury, Earth History, Vol. III, pp. 437–445.

to an increase in numbers of individuals, and partly to better conditions of preservation.

The general aspect of life was cosmopolitan, though it was not the same everywhere. It varied with the physical evolution of the continent, and largely as the result of it. The variations assumed three general phases: (1) adaptation to the immediate physical environment, particularly the nature and depth of the sea-bottom; (2) modification by auto-evolution within areas isolated by barriers (*provincial evolution*); and (3) modification toward a universal type through intermigration (*cosmopolitan development*).

(1) Rocky, sandy, muddy, and calcareous bottoms had their appropriate life, as did also tracts of shallow and deep water. The faunas adapted to these special conditions were not altogether unlike, for some animals, particularly free-swimmers, were indifferent to them.

(2) Although the sea covered a large part of the continent, affording facilities for the migration and mingling of faunas, there is evidence of some separation into zoölogical provinces. This was probably due partly (a) to barriers in the form of shoals, bars, and spits, (b) to ocean-currents with their attendant differences in temperature, and (c) to variations in the saltness of the waters.

(3) Notwithstanding local and provincial modifications, the progress of Ordovician life in the American continent seems to have been, on the whole, in the direction of cosmopolitanism, especially in the shallow water faunas of the great interior of the continent. This was due, primarily, to the wide epicontinental seas, which permitted free migration.

The Ordovician system contains an exceptionally large number of fossils of free-floating graptolites[1] (Fig. 343). Their remains are mingled with the fossils of shallow-water life, showing that they swam over the epicontinental seas freely. The Ordovician graptolites are nearly identical in Europe, North America, and Australia. The history of individual species was short, geologically speaking, and hence the succession of species marks the progress of events in all parts of the ocean. During the lifetime of the graptolites (limited to the late Cambrian, Ordovician and Silurian), a score of successive zones, each characterized by particular species, have been

[1] It is not universally agreed that all graptolites were floating forms at all stages, but there seems to be little doubt that they usually were in their young stages at least.

identified. One of these zones falls in the Cambrian, eight in the Ordovician, and eleven in the Silurian. If these be taken as chronological bench-marks, the successive horizons of the different continents may be correlated accurately, and the progress of life in the various quarters of the globe referred to a common standard.

**Marine life.** The known faunas of the Ordovician consist almost wholly of marine invertebrates, among which trilobites and brachiopods hold the leading places. Brachiopods are most numerous, trilobites highest in organization, and cephalopods most powerful; but the foreshadowings of a new dynasty are at hand, for remains of fish are found in this system.

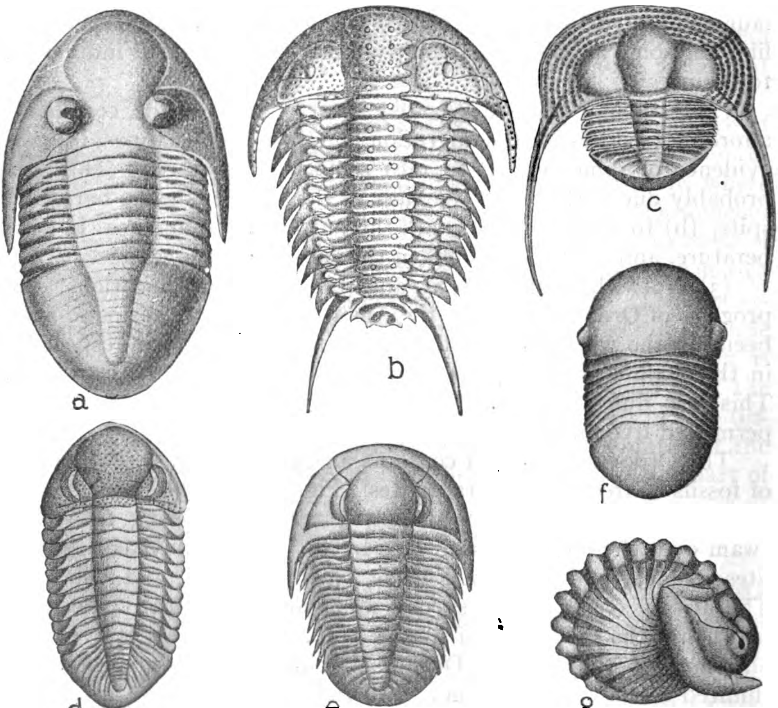



Fig. 335. Ordovician Trilobites: *a*, *Isotelus maximus* Locke; *b*, *Ceraurus pleurexanthemus* Green; *c*, *Trinucleus ornatus* Sternberg; *d*, *Pterygometopus callicephalus* (Hall); *e*, *Pröetus parviusculus* Hall; *f*, *Bumastus trentonensis* (Emmons); *g*, *Calymene callicephala* Green.

*Trilobites* reached their climax in the Ordovician period, more than half of all the known genera being represented in the Ordovician system. But few of them lived over from the Cambrian. In the next period the numbers fell off a full half, and the decline continued until the tribe became extinct. The general aspect of the trilobites at the high tide of their career is fairly illustrated in Fig. 335. There was little or no increase in average size, as compared with their Cambrian forbears. Some individuals had a length of 18 inches; but this size was equaled and even surpassed by some of their predecessors.

*Cephalopods.* The largest, most powerful, and perhaps most predaceous forms of Ordovician life, seem to have developed into

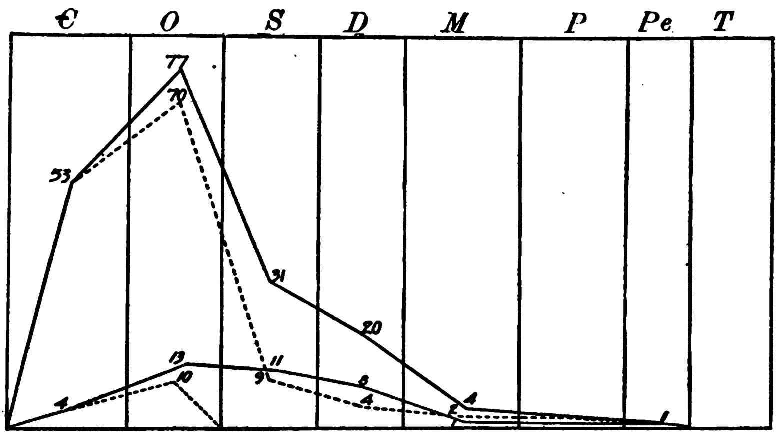



Fig. 336. The two upper curves represent the history of the trilobites according to genera, the full line indicating the total number of genera, and the dotted line the number of new genera introduced. The two lower curves present the same data for the families of the trilobites. Data for families from Beecher in the Zittel-Eastman text-book of Paleontology, Vol. I. Data for genera, somewhat incomplete, from Zittel's "Handbuch der Paläontologie." €, Cambrian; *O*, Ordovician; *S*, Silurian, etc., *Pe*, Permian, and *T*, Trias.

prominence suddenly. Unless the fishes, of which little is known, contested their supremacy, they were doubtless the undisputed masters of the sea. Their general aspect is seen in Fig. 337. The dominant type, as well as the most primitive one, had long, straight, gently tapering shells (Fig. 337, *c* and *f*) divided into chambers by plane partitions (*septa*). Even in the Ordovician period there was a wide departure from this ideal simplicity. There were curved

forms and coiled forms, some of which resemble the *Nautilus* of to-day (Fig. 337, *e*). Straight forms predominated, however, and the sutures (junctions of the septa with the outer shell) were simple, in marked contrast with some of those of later periods.

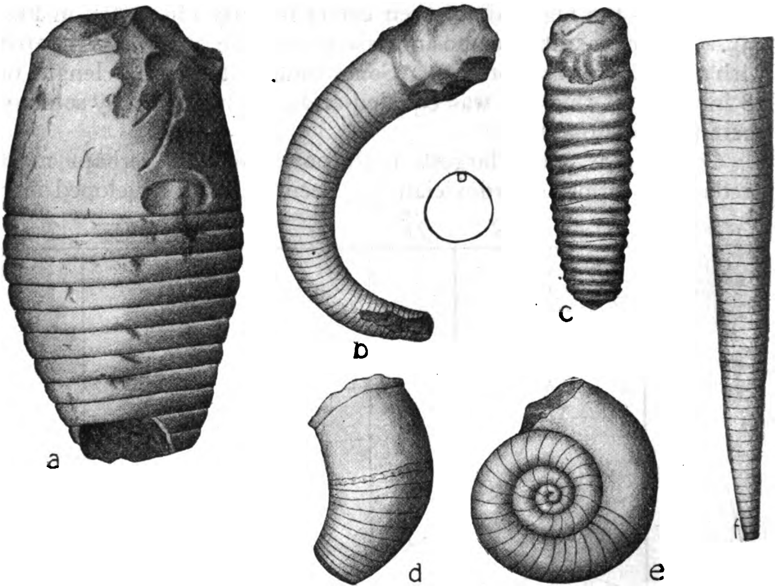



Fig. 337. Ordovician Cephalopods: *a*, *Poterioceras apertum* Whiteaves; *b*, *Cyrtoceras neleus* Hall; *c*, *Orthoceras bilineatum* Hall; *d*, *Oncoceras pandion* Hall; *e*, *Trocholites ammonius* Conrad; *f*, *Orthoceras sociale* Hall.

In size, Ordovician cephalopods were probably never surpassed by representatives of their class. Some of the shells were 12 or 15 feet in length, and a foot (maximum) in diameter. From this great size they ranged down to or below the size of a pipe-stem. Unlike many mollusks, cephalopods were free swimmers. *Gastropods*, the kin of modern snails, were well represented in the early Ordovician fauna by diverse forms (Fig. 338). Few types of early Paleozoic life so closely resembled their modern relatives. *Pelecypods* (Fig. 338), the class to which clams and oysters belong, were subordinate to gastropods. Like their modern relatives, the Ordovician pelecypods seem to have been fond of muddy and sandy bottoms, for

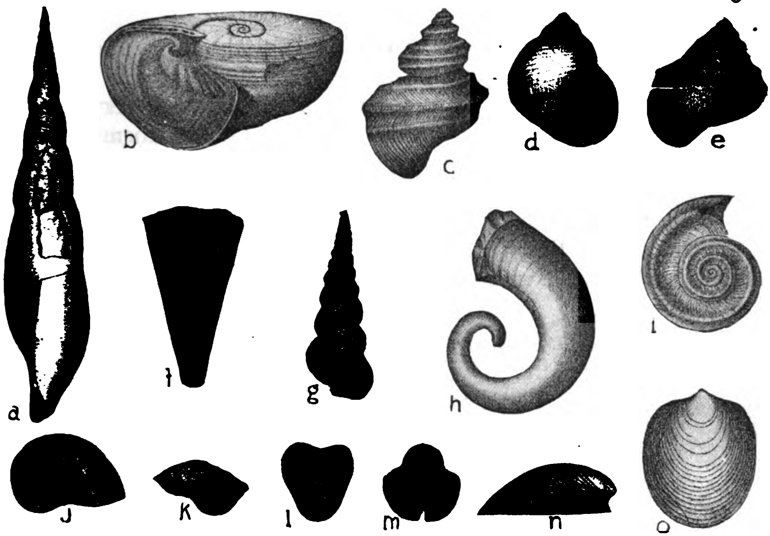



Fig. 338. Ordovician Gastropods: *a*, *Subulites regularis* U. and S.; *b*, *Maclurea logani* Salter; *c*, *Lophospira helicteres* (Salter); *d*, *Cyclomena bilix* (Conrad); *e*, *Schizolopha textilis* Ulrich; *f*, *Conularia trentonensis* Hall; *g*, *Hormotoma gracilis* (Hall); *h*, *Eccyliomphalus triangulus* Whitfield; *i*, *Helicotoma planulata* Salter; *j*, *Cyrtolites ornatus* Conrad; *k*, *Raphistomina lapicida* (Salter); *l*, *Protowarthia cancellata* (Hall); *m*, *Bellerophon clausus* Ulrich; *n* and *o*, *Archinacella cingulata* Ulrich.

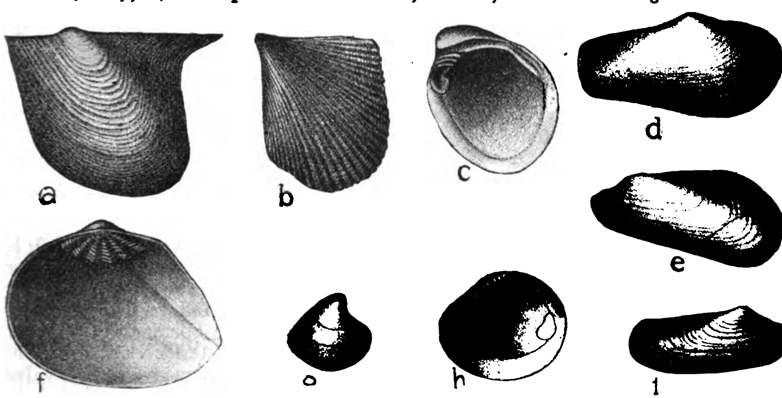



Fig. 339. Ordovician Pelecypods: *a*, *Pterinea demissa* (Conrad); *b*, *Byssonychia radiata* (Hall); *c*, *Vanuxemia dixonensis* M. and W., interior of right valve, showing the hinge and muscular impressions; *d* and *e*, *Ctenodonta nasuta* (Hall); *f*, *Lyrodesma cincinnatiensis* Hall, interior of right valve, showing a primitive type of hinge; *g*, *Ctenodonta recurva* Ulrich; *h*, *Ctenodonta pectunculoides* Hall; *i*, *Rhytimya radiata* Ulrich, exterior of right valve.

they are rather rare in the limestone beds of the early and middle Ordovician, and more abundant in the later shales.

*Brachiopods* were still very abundant. Some were very similar to those of the Cambrian; but the higher, articulate forms (valves of the shell articulating) greatly outnumbered them. Among the articulate forms, the length of the hinge was increased, apparently affording a better means of resisting the attempts of enemies to reach them by sliding or rotating the valves past one another (*i* and *p*, Fig. 340), while in others the margins of the valves were

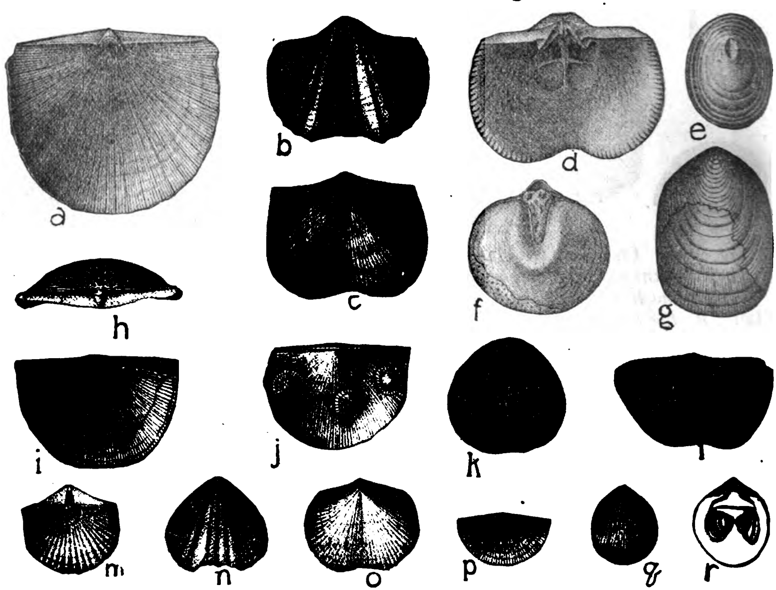



Fig. 340. ORDOVICIAN BRACHIOPODS: *a*, *Rafinesquina alternata* (Emmons); *b*, *Platystrophia lynx* (Eich.); *c*, *Hebertella sinuata* (Hall); *d*, *H. sinuata* (Hall), interior view of the brachial valve, showing muscular impressions and hinge; *e*, *Schizotreta ovalis* H. and C., a pedicle valve; *f*, *Trematis millepunctata* Hall, pedicle view of a complete shell, showing the unmodified notch-like pedicle opening; *g*, *Lingula rectilateralis* Emmons; *h-i*, *Strophomena subtenta* Conrad, posterior view of a complete shell, showing the hinge-line, etc., and the exterior of the concave pedicle valve (i); *j*, *Crania lælia* Hall, brachial views of four individuals attached to another shell; *k*, *Schizocrania filosa* (Hall), a brachial valve; *l*, *Leptæna rhomboidalis* Wilck, the pedicle valve; *m*, *Orthis tricenaria* Conrad, exterior of the brachial valve and the cardinal area of the pedicle valve; *n*, *Rhynchotrema capax* Conrad; *o*, *Dalmanella testudinaria* (Dal.), brachial view; *p*, *Plectambonites sericeus* (Sow.), brachial view; *q*, *Catazyga headi* (Bill.), brachial view; *r*, *Zygospira recurvirostris* (Hall), interior of a brachial valve, showing the spiral brachidium in position. Compare Fig. 324.

notched so that the valves interlocked. In addition to these devices for preventing the opening of the shell, there was generally a thickening of the valves, and in many cases a ribbing of the exterior, giving strength without needless weight. These devices seem to imply that the enemies of the brachiopods had increased in effectiveness, but the abundance of the brachiopods implies that their enemies did not gain the mastery.

*Bryozoans* (Fig. 341), kin to the brachiopods (p. 686) were very unlike them in external form, in habits, and in their hard

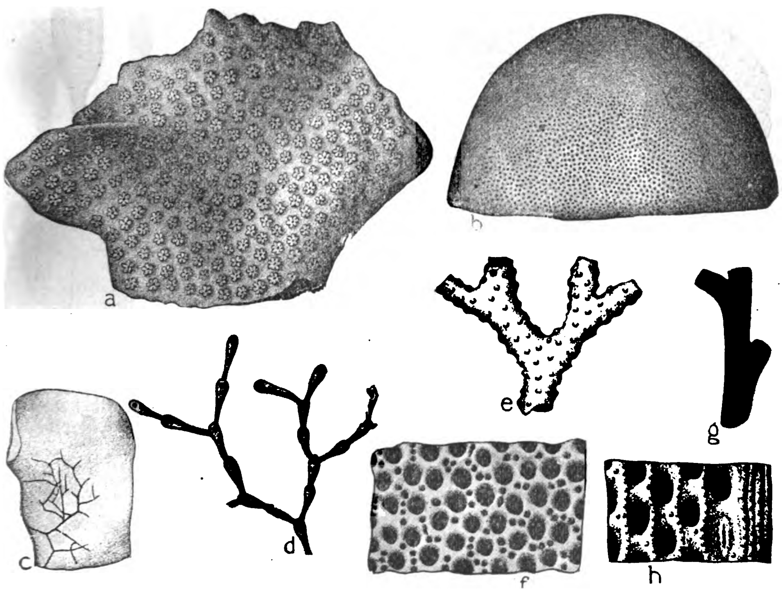



Fig. 341. Ordovician Bryozoans: *a*, *Constellaria polystomella* Whitfield; *b*, *Crepipora hemispherica* Ulrich; *c*, *Stromatopora delicatula* (James); *d*, a part of *c*, enlarged; *e*, *Callopora pulchella* Ulrich, *f*, a part of *e* enlarged; *g*, *Rhinidictya mutabilis* Ulrich, *h*, a part of *g* enlarged.

secretions. They lived in colonies, which secreted calcareous material. These secretions resemble coral so closely that they have been mistaken for it. In the middle and later portions of the period, the secretions of bryozoa contributed much of the limestone.

*Echinoderms* (p. 686), represented now by such forms as starfish and sea-urchins, were plentiful. The *cystoids* reached their climax before the close of the period; the *crinoids* became prominent,

and the starfish and sea-urchin types had made their appearance. The cystoids (a, b and c, Fig. 342), with their irregular forms, were the most primitive, and gave place in time to the more symmetrical crinoids (Fig. 342, *d* to *k*), which may be likened to star-fishes turned

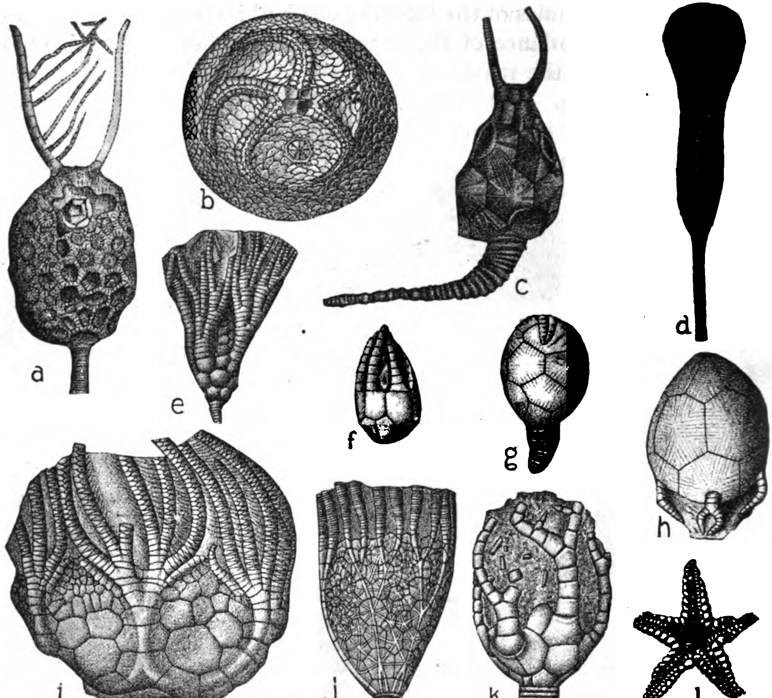



Fig. 342. ORDOVICIAN ECHINODERMS: *a*, *Comarocystis punctatus* Billings; *b*, *Lepidodiscus cincinnatiensis* (Roemer); *c*, *Pleurocystis filitextus* Billings; *d*, *Ectenocrinus grandis* (Hall); *e*, *Dendrocrinus polydactylus* (Shumard); *f*, *Hybocrinus tumidus* Billings; *g*, *Lepadocystis moorei* (Meek); *h*, *Carabocrinus vancortlandti* Billings; *i*, *Archæocrinus desideratus* Billings; *j*, *Glyptocrinus decadactylus* Hall; *k*, *Anomalocrinus incurvus* M. and W.; *l*, *Palæaster simplex* Miller. *a*, *b* and *c* are cystoids, *d-k* are crinoids, *l* is a star-fish.

face uppermost and fixed to the sea-bottom by a calcareous stem attached to the center of the back. Crinoids so closely resembled a flower in form, that the familiar name "sea-lily" is not inappropriate.

*Corals* are few in the lower part of the system, and though more abundant in higher beds, are nowhere a leading part of the fauna.

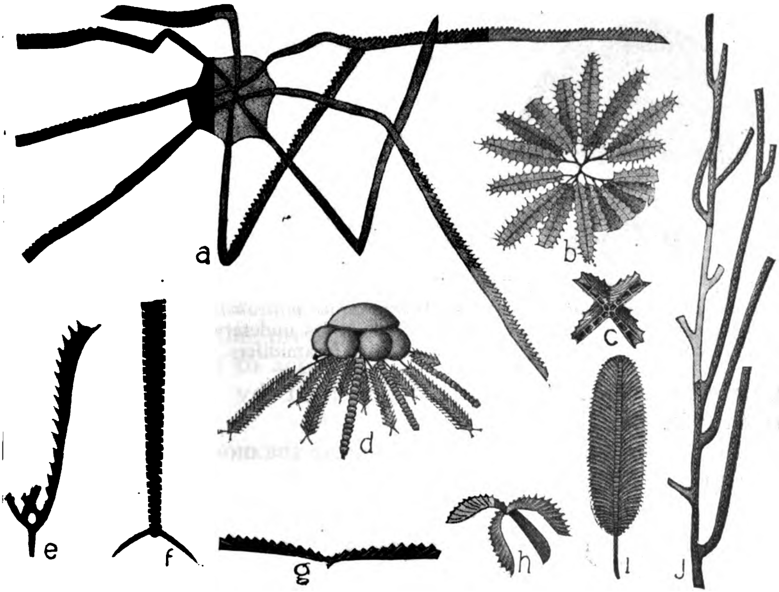



Fig. 343. Ordovician Graptolites: *a*, *Dichograptus octobrachiatus* (Hall); *b*, *Reteograptus eucharis* Hall; *c*, *Phyllograptus ilicifolius* Hall; *d*, *Diplograptus pristis* (Hall) (restored by Ruedemann); *e*, *Tetragraptus fruticosus* (Hall); *f*, *Climacograptus bicornis* (Hall); *g*, *Didymograptus nitidus* Hall; *h*, *Tetragraptus bigsbyi* (Hall); *i*, *Phyllograptus typus* Hall; *j*, *Holograptus richardsoni* (Hall).

Most of them belonged to the simpler horn-shaped type (Fig. 344, *a*), but compound and colonial corals were present. The most important development of the cœlenterates was the rise of the *graptolites* (Fig. 343), whose important function in correlation has been referred to (p. 377).

Some *sponges* (Fig. 345) attained notable size. The record of *annelids* (worms) is more meager than in the Cambrian, perhaps because the calcareous sea-bottom of the Ordovician was less congenial to them than the

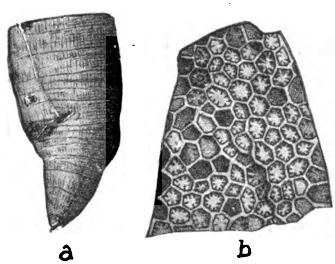



Fig. 344. Ordovician Corals: *a*, *Streptelasma corniculum* Hall; *b*, *Columnaria alveolata* Goldf. Both simple and compound corals lived, but they did not form great reefs as in later periods.

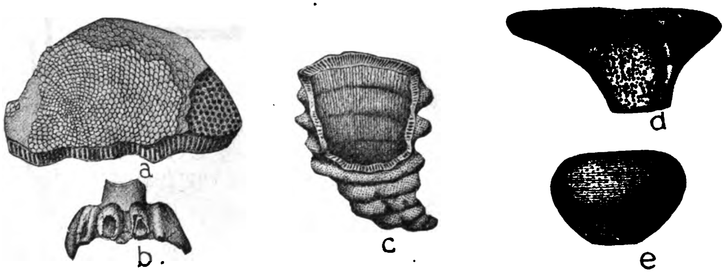



Fig. 345. ORDOVICIAN SPONGES: *a, Receptaculites occidentalis* Salter; *b, Brachiospongia digitata* Beecher; *c, Archæcyathus minganensis* Billings; *d, Protospongia maculosa* U. and E.; *e, Ischadites*, species undetermined. *Receptaculites* and *Ischadites* were formerly regarded as giant foraminifers.

Cambrian sands. They are represented by burrows and by teeth (Fig. 346).

Fragmentary fossils of *fishes* constitute the most striking innovation in the record of the marine life of the period. These have

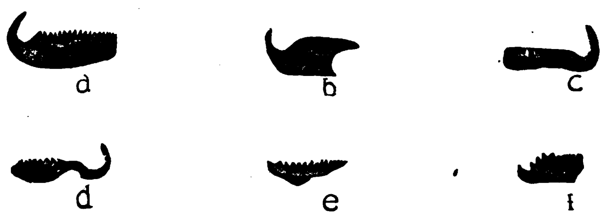



Fig. 346. JAWS OF ORDOVICIAN ANNELIDS, highly magnified: *a, Arabellites cornutus* Hinde; *b, Glycerites sulcatus* Hinde; *c, Eunicites gracilis* Hinde; *d, Arabellites ovalis* Hinde; *e, Eunicites varians* (Grinnell); *f, Oenonites rostratus* Hinde.

been found in a few localities only, notably near Canyon City, Colo., and in the Bighorn Mountains of Wyoming. As in the Cambrian, a vast supply of unrecorded *vegetation* must be postulated to have supplied food for the animals. To provide for organisms that preyed upon one another in succession, from plants up to the master forms of the predaceous animals, there were doubtless many species not now known. The fact that vegetal tissues are not found among fossils, save in rare cases, probably signifies that the bacteria concerned in the decomposition of organic matter were abundant.

**General advancement.** It seems clear that the adaptation of the various forms of life to one another and to their physical environment had reached a higher stage of adjustment than in the Cam-

brian, an adjustment not greatly inferior to that which now prevails among the corresponding orders. Higher types within the same orders have been developed since in many cases, but some of the Ordovician forms have since suffered degeneration. The Ordovician ancestors of the barnacle, for example, free-moving, active forms, were doubtless superior to their sessile descendants of ill-repute.

**Land life.** But few relics of land plants, and these somewhat doubtful, have been found in the system, and they reveal but little.

The oldest relic of *insect life* now known is a rather obscure wing found in the shales of the Upper Ordovician of Sweden. It is referred to the order of *Hemiptera* (bugs). The existence of flying insects implies the presence of vegetation, and of atmospheric conditions suited to active, air-breathing organisms.

### *Succession of Faunas*

There was a succession of Ordovician faunas, somewhat unlike one another, just as there was a succession of Cambrian faunas. These may be distinguished roughly as the Lower, Middle, and Upper Ordovician faunas. In some places, the late Cambrian and early Ordovician faunas merge into one another without sharp definition. In general, the Mid-Ordovician fauna was more prolific than that which preceded, if we may judge from the fossils. The Mid-Ordovician fauna, too, was distinctly cosmopolitan. The Upper Ordovician fauna was similar to its predecessor, from which it descended, but clear-water forms were less dominant.

*Map work.* See note at end of last chapter. The folios serviceable for the Cambrian system are serviceable also for the Ordovician. See also Exercise IX in *Laboratory Exercises in Structural and Historical Geology*.

# CHAPTER XVII

## THE SILURIAN (UPPER SILURIAN) PERIOD

### FORMATIONS AND PHYSICAL HISTORY

The changes which brought the Ordovician period to a close marked also the inauguration of the Silurian. These changes included movements which affected (1) small areas intensely, and (2) broad areas slightly. From the standpoint of continental history, the latter were the more important. These changes were accomplished slowly, and after they had taken place, the area of land in North America was greater than at any time since the early Cambrian. The increase in land meant lengthened streams, and presumably increased erosion.

It is safe to assume that at the opening of the period clastic sediments were accumulating about the immediate borders of the lands, and as far out as waves and currents were able to transport detritus, and that elsewhere sediments of organic origin were relatively more important. Though sedimentation was interrupted in regions which emerged from the sea at the close of the Ordovician period, the interruption was not universal, and Silurian strata are locally conformable on the Ordovician in the continents, and generally, it is presumed, in the ocean basins.

In New York, the Silurian is subdivided as follows[1]:

| | | |
|---|---|---|
| Silurian | Cayugan (Upper Silurian) | Manlius limestone<br>Rondout waterlime<br>Cobleskill limestone<br>Salina beds |
| | Niagaran (Middle Silurian) | Guelph dolomite<br>Lockport limestone<br>Rochester shale<br>Clinton beds |
| | Oswegan (Lower Silurian) | Medina sandstone<br>Oneida conglomerate (and perhaps the Richmond beds) |

[1] There is infelicity in the use of the terms Lower, Middle, and Upper Silurian for the subdivisions of the system, since Lower Silurian was long used as a synonym for Ordovician, and Upper Silurian for Silurian, as that term is here employed.

Each of the three series is made up of several formations, but the subdivisions of one place do not fit another. A brief sketch of the nature and distribution of the principal subdivisions of the system affords an outline of the history of the continent during the period.

### *Silurian of the East*

**Oswegan series.** This series is known chiefly in New York,[1] both the Oneida and the Medina formations appearing at the surface south of Lake Ontario. Their equivalents may recur in the western part of the Appalachians farther south. The Oneida consists of conglomerate and sandstone, and the Medina of sandstone and shale. The sediments of these formations appear to have been deposited in a shallow interior sea, as shown by fossils, and by the cross-bedding, ripple-marks, etc., which affect them. Both formations are probably continuous beneath younger strata over considerable areas south of Lake Ontario, and west of the Appalachians,[2] and the Medina is more wide-spread than the Oneida.

**Niagaran series.** The *Clinton formation* overlies the Medina conformably, but has a wider distribution, extending westward to Lake Huron and Indiana, and perhaps to the Mississippi, and southward, in the Appalachians, to Alabama and Georgia. Beds of Clinton age have been recognized in Nova Scotia and at a few other places northeast of the United States, where marine sedimentation was probably continuous through the Ordovician and Silurian periods. In the Appalachian Mountains, the formation is largely of sandstone and shale. In western New York and farther west, much of it is limestone.

One of the features of the formation is its *iron ore*, generally in the form of hematite ($Fe_2O_3$). The ore is known at many points between New York and Alabama, as far west as Wisconsin, and in Nova Scotia. It is interstratified with other beds of the formation, and is usually believed to have been accumulated by chemical precipitation in lagoons or marshy flats.

The *Niagara formation* (subdivided in New York, p. 388), extends farther west than any of the preceding Silurian formations, showing that the submergence begun earlier still continued in the upper Mississippi basin. The falls of Niagara River are over the

[1] The formations of eastern New York and New Jersey formerly classed as Oneida, are of Salina age. Hartnagle, Bull. 107, N. Y. State Mus.

[2] Perhaps the Richmond beds, the Maquoketa shales, etc.

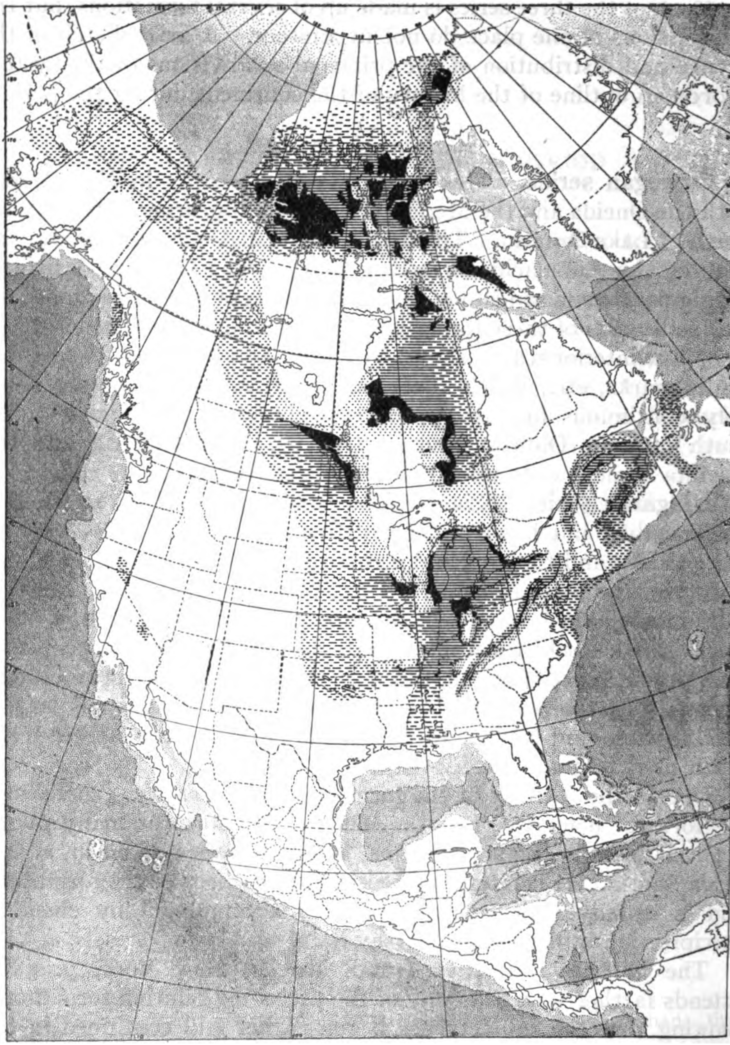


Fig. 347. Map showing the outcrops of the Niagara formation, and at the same time the general relations of land and water during the Niagara epoch. The various sorts of shading on the map correspond with those on earlier maps (see p. 345).

limestone of this series (Fig. 76). North of Missouri, the formation is not known far west of the Mississippi, but it extends into Missouri, Arkansas, and perhaps even to the Arbuckle Mountains of Oklahoma. It is found also in western Texas. The southern border of the interior sea in which this formation was deposited is not known, but it may have been separated from the Gulf of Mexico, by a land barrier (Fig. 347).

A significant feature of the distribution of the Niagara formation is its great development in northerly latitudes (p. 390). The known patches in the north appear to be remnants of a once continuous formation, and since the fossils are much like those of northern Europe, it is inferred that there was shallow-water connection between the Mississippi basin and northern Europe by way of the Arctic islands, which permitted the intermigration of the shallow-water sea-life of the two regions.

East of the Appalachians and west of the Mississippi the distribution of Niagaran strata is not known in detail. Their exact equivalents have not been identified in the West. West of New York the formation is mainly limestone. It is the oldest formation in which well-developed *coral reefs* have been identified, though coral-secreting polyps had lived before (p. 385). Reefs are known in eastern Wisconsin, Indiana, and elsewhere.

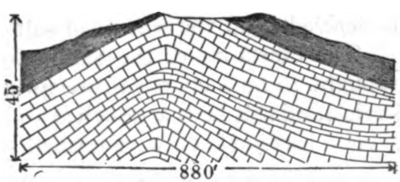


Fig. 348. The Wabash dome in the Niagara limestone. (Kindle.)

In the east where the Niagara is known, it has a thickness of but 100 to 300 feet, while in Wisconsin it attains a maximum of 800 feet (perhaps including some Clinton), all of which is limestone. While the Niagaran beds of the interior are in general nearly horizontal, they are domed in many places, giving the beds a high dip (Fig. 348), as at various points about the south end of Lake Michigan.

**Cayugan series.** The Salina formation, which overlies the Niagaran series in parts of New York, Pennsylvania, Ohio, Michigan, and Ontario, is much less widespread, indicating the emergence of a considerable area in the Mississippi basin at the close of the Niagaran epoch. The formation embraces all common sorts of sedimentary rock, and in addition rock salt, and gypsum. Shale is the most abundant sort of rock, and seems to have originated after the fashion

of shales in general, but the fewness of its fossils points to deposition under conditions unfavorable for life. The salt is widely distributed. In New York alone it occurs at many points within an area of 9,000 to 10,000 square miles. Single beds of it are locally 40 to 80 feet thick. In places, several beds occur one above another, interstratified with other kinds of rock, and their aggregate thickness reaches as much as 100 feet in places. Near Cleveland, four salt beds, 50 feet and less in thickness, are interstratified with 500 feet of shales.

The salt beds seem to imply the existence of great lagoons or inclosed seas. Deposits of gypsum are made under about the same conditions as salt beds. Had the climate of this region been as moist as now, lagoons could not have been abnormally saline. Occasional incursions of the sea, bringing in new supplies of salt water, followed by periods when the lagoons were cut off from the sea, and when they suffered rapid evaporation, would seem to meet the conditions demanded for the salt. So also would a slight continuous connection with the sea, such that the inflow of sea-water into the basin was less than the excess of evaporation over precipitation. A bed of salt 40 feet thick implies the evaporation of some 3,000 feet of normal sea-water. Much of the commercial salt which comes from New York is derived from the waters of salt wells.

The limestone of the Salina contains few fossils, and has been thought to be a chemical precipitate. The relations of limestones, shales, and salt beds are such as to indicate that the sites where these several sorts of rock were formed shifted from time to time, as if by gentle crustal warping.

Above the Salina proper of New York, there is a thin (150 feet maximum) series of limestones (p. 388), more widespread than the Salina. Its equivalent extends westward through Ohio to Indiana and Wisconsin. Both its distribution and its character show that the eastern interior was more generally submerged than during the deposition of the salt-bearing series which preceded.

The Helderberg formation, formerly regarded as a part of the Silurian system, is here classed with the Devonian.

**Summary.** As in the preceding systems of the Paleozoic, the greatest thicknesses of Silurian strata (estimated at about 5,000 feet, maximum) are in the Appalachian region. Over the interior, the system is measured by hundreds of feet rather than by thousands. In keeping with these variations of thickness, the system is largely

of clastic sediments in the Appalachian belt, while in the interior it is largely of limestone. The site of sedimentation in the east was a sort of trough (the Appalachian trough) shut off from free communication with the interior sea, but connected narrowly with the Atlantic, perhaps by way of the present Chesapeake region. Since most of the sediments of this trough were deposited in shallow-water, they are thought to indicate that the trough was sinking at a rate comparable to that at which the sediments accumulated. With the down-warping of the trough, there may have been up-warping of the adjacent lands to the east, which supplied the sediments.

The history of the Silurian period, as now understood, involves, (1) a general submergence of the eastern part of the United States west of Appalachia, by which the sea became more and more widespread until the close of the Niagaran epoch; (2) a partial withdrawal of the sea from the same area in the Salina epoch; and (3) an extension of the sea at the close of that epoch.

### *Silurian of the West*

At various points in the West, there are sedimentary beds, poor in fossils, between the known Ordovician below and the Devonian above. The character of the fossils being indecisive in many places, the age of the beds is open to question. Some of them may be Silurian. If the Silurian is really absent from all the areas where its presence is not now known, it would appear that a large part of western North America was land during the Silurian period. Silurian beds are however known in Southern California, Nevada, Utah, and Alaska, and perhaps in the Canadian Rockies, and their distribution may be more widespread than has been supposed.

### *General Considerations*

**Igneous rocks.** At few points in North America have igneous rocks of Silurian age been identified. Silurian formations are locally affected by intrusions, but their dates are generally uncertain. Some of the igneous rocks of New Brunswick are thought to be of Silurian age, and perhaps some of those of Nova Scotia and Maine.

**Close of the period.** The geographic changes at the close of the Silurian were less than those at the close of the Ordovician, and the system is less distinctly separated from the Devonian above than from the Ordovician below.

**Climate and duration.** There is nothing to indicate great

diversity of temperature in the Silurian period, and much to suggest that uniformity extended through great ranges of latitude, for the fossils of warm-temperate regions are in part the same as those in Arctic regions. Some regions appear to have been temporarily very arid. This probably was one of the shorter Paleozoic periods.

### *Foreign*

In Europe the Silurian strata have a distribution similar to that of the Ordovician, though they are wanting in some regions where the latter are present. The fact that the Silurian strata do not appear at the surface over wide areas does not indicate their general absence, so much as their widespread concealment. In most of the northern part of Europe, outside of Britain, the system has been little deformed. In contrast with the Silurian rocks of the northern province, those of the southern are much deformed.

There were important geographic changes in some parts of Europe at the close of the period, as shown by the unconformity between the Silurian and Devonian systems in some places (Great Britain and Ireland). In some parts of western Europe there were overthrust faults of great extent. Locally (Scotland) the thrust was as much as ten miles,[1] and had for a result, the thrusting of Cambrian and even Archean formations, over the Silurian.

The Ordovician and Silurian of other continents have not been generally distinguished. Equivalents of the two systems probably occur in all the less well-known continents.

## LIFE

The extensive withdrawal of the sea from North America at the close of the Ordovician period reduced the area of shallow water available for the life which needed it. The severe repressive evolution which followed was the great biological feature of the transition from the Ordovician to the Silurian. With the re-invasion of the interior by the mid-Silurian sea, there followed an expansional evolution of the shallow-water fauna which constitutes the great biological feature of the middle of the period. Toward its close, there was restriction of the epicontinental sea, complicated with intense salinity in the eastern interior, and there followed a second repressive evolution through which the Silurian fauna passed into the Devonian.

Theoretically, the history of the land life should have been the

[1] Quart. Jour. Geol. Soc., 1884 and 1888.

reciprocal of that of the sea; for as the sea contracted, the land expanded, and an expansion of land life should have run hand in hand with the restriction of sea life. The record of land life is too meager to demonstrate that this was the fact. In so far as the climate was arid, it was unfavorable for abundant land life.

**Transition from the Ordovician.** Of the shallow-water life of the early Silurian there is but meager record. The eastern shore of the continent was then farther east than now, and the deposits there are buried and inaccessible. The western border may have been submerged, but the fauna there is little known.

In addition to the lessened area available for shallow-water life, the conditions probably were less favorable than before. The increased detritus brought to the sea probably inhibited some forms of life, injured others, and helped but few. Some of the basins and bays were doubtless too fresh and some too salt. These general considerations may explain the meagerness of the faunas of the early Silurian strata. But conditions were not adverse everywhere. In the Gulf of St. Lawrence, Ordovician species lived on for varying lengths of time, and mingled with Silurian species as they developed, and so recorded the transition.

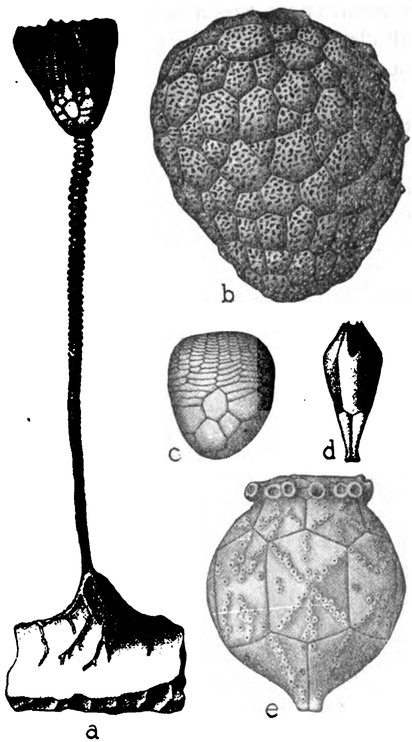



Fig. 349. Silurian Echinoderms: *a*, *Eucalyptocrinus crassus* Hall, a complete crinoid, showing roots, stem, and body; *b*, *Holocystites adiapatus* Miller, a cystoid with irregularly arranged plates and scattered pores; *c*, *Lecanocrinus macropetalus* Hall, an articulate crinoid; *d*, *Troostocrinus reinwardti* (Troost), showing the typical bud-like form of a blastoid; *e*, *Caryocrinus ornatus* Say, a cystoid with regularly arranged body plates. Pores in radiating lines from centers of plates.

**Mid-Silurian fauna.** As the sea slowly overspread the continent toward the middle of the period, the increasing room and more congenial conditions for most forms of shallow-water life resulted in an expansional evolution which produced the Niagara fauna. The families and classes were much the same as in the Ordovician period, but most of the genera were new, and nearly all the species. In general there was a biological advance, though this was not true of all classes. Only the more conspicuous features of the changes will be noted.

A distinguishing feature of the Silurian fauna was the rich and varied development of the echinoderms, especially the *crinoids* (Fig. 349). They attained such abundance in certain localities that their fragments form the larger part of the limestone. These spots were veritable "flower-beds" of "stone lilies," where beautiful and varied forms grew in groves, as it were. *Cystoids* were still abundant, and *blastoids* appear for the first time. *Starfishes*, *serpent-stars* and *echinoids* were unimportant elements in the fauna.

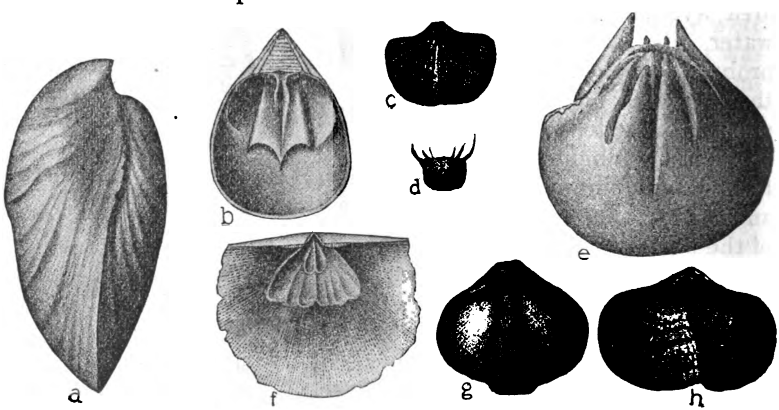



Fig. 350. Silurian Brachiopods: *a*, *Pentamerus oblongus* Murch., lateral view of an interior cast; *b*, *Trimerella acuminata* Bill., the interior view of a pedicle or ventral valve, showing the elevated platform for muscular attachment excavated beneath; *c*, *Spirifer niagarensis* (Con.), exterior view of the brachial or dorsal valve, with the cardinal area and beak of the pedicle valve showing above; *d*, *Chonetes cornutus* (Hall), exterior view of ventral valve, showing the cardinal spines; *e*, *Trimerella ohioensis* Meek, the internal cast of a highly differentiated inarticulate brachiopod, showing the fingerlike casts of the excavations beneath the elevated muscular platforms; *f*, *Stropheodonta profunda* Hall, interior of the ventral valve, showing muscular impressions; *g*, *Spirifer radiatus* Sow.; *h*, *Streptis grayi* (Dav.), exterior view of the brachial valve, showing the cardinal area and beak of the opposite valve, and the peculiar twisted form of the shell.

*Brachiopods* (Fig. 350) lived on from the Ordovician with no loss of prestige, though most species and many genera were new. The Silurian brachiopods showed some notable advances in structure. On the whole they were more robust and gave more obvious signs of abounding vitality than before; but along with the progressive developments there were some retrograde modifications.

*Among mollusks, cephalopods* appear to have remained the most powerful inhabitants of the seas. Straight forms were still common, but curved and coiled ones were more numerous. Their shells were more highly ornamented than before, though still plain in comparison with some of their successors. The apertures of the shells of most Ordovician species were circular or oval, but in the Silurian species many of them were curiously constricted (*b*, Fig. 351), especially among the small curved and coiled species. The

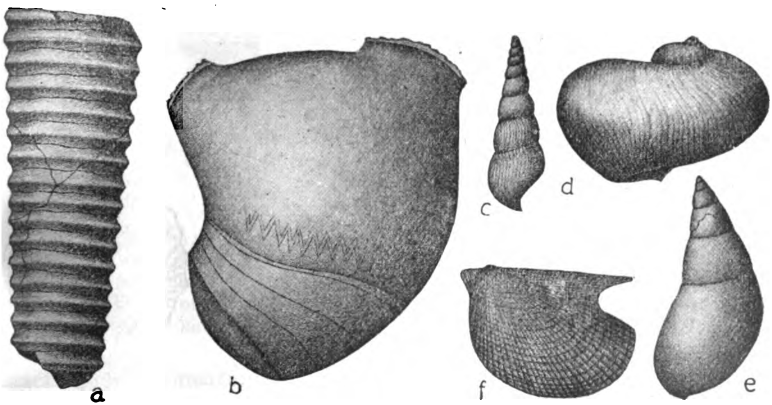



Fig. 351. Silurian Mollusks: *a* and *b* are cephalopods. *a*, *Orthoceras annulatum* Sow., a straight chambered shell with annulations; *b*, *Phragmoceras nestor* Hall, lateral view of a curved chambered shell with peculiar constricted aperture. *c*, *d*, and *e* are gastropods; *c*, *Loxonema leda* Hall; *d*, *Platyostoma niagarensis* Hall; *e*, *Subulites ventricocus* Hall; *f*, *Pterinea emacerata* (Con.), exterior view of left valve of a pelecypod.

constriction appears to have been a protective device. *Gastropods*, fairly well represented in the Cambrian period and amply in the Ordovician, did not increase greatly in the Silurian. They show advance in the preponderance of elevated spires, in increased variety of form, and some of them in greater size; but the older types were still plentiful. *Pelecypods* (*f*, Fig. 351) were not more plentiful than in the Ordovician.

The prominence gained by *corals* (*polyps*) in suitable situations is one of the notable features of the Silurian fauna. In the Ordovician period, simple forms predominated over compound, but the ratio was now reversed. Among the notable types was the chain

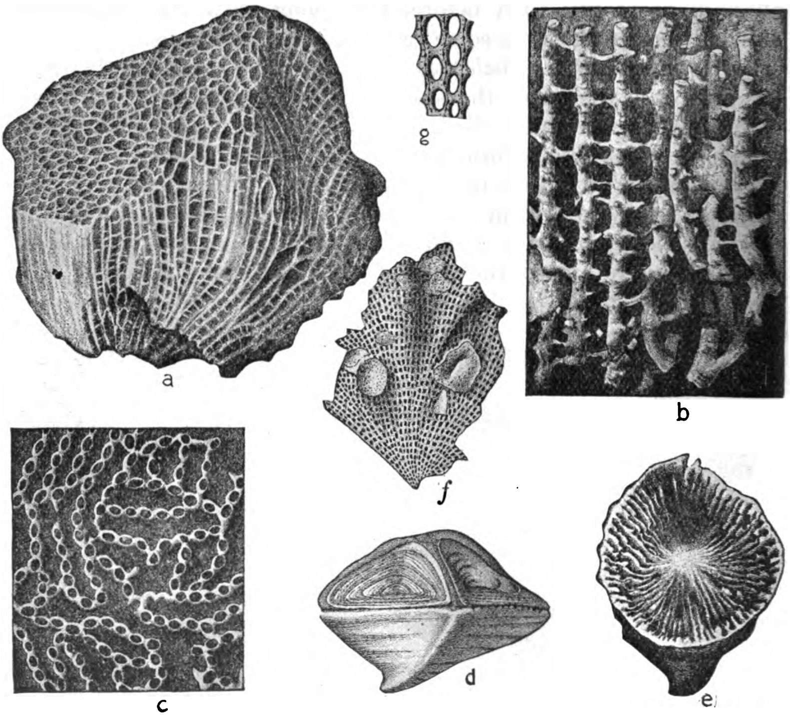



Fig. 352. Silurian Corals and Bryozoans: *a-e* are *corals*. *a*, *Favosites occidens* Whit.; *b*, *Syringopora verticillata* Goldf.; *c*, *Halysites catenulatus* Linn.; *d*, *Goniophyllum pyramidale* (His.); *e*, *Zaphrentis umbonata* Roming. Bryozoans, *f* and *g*, *Fenestella parvulipora* Hall.

coral (*c*, Fig. 352), which had appeared in the Ordovician; the honeycomb coral (*a*); the organ-pipe coral (*b*); and the cup coral (*e*). A most peculiar simple coral was quadrangular, and its top provided with a cover (operculum) of four triangular plates hinged to the four sides of the cup's margin. When closed they formed a pyramid over the cup (*d*, Fig. 352, only two opercular plates shown). This was a protective device unknown among modern corals. With their

increase in abundance, corals acquired the habit of associating themselves together. This resulted in the formation of reefs. The known reefs appear to have been of the barrier type formed some distance from shore. The reef-forming habit appears to have been local rather than general.

Among *trilobites*, no new families appeared, though there were some new genera and many new species; but the new forms did not

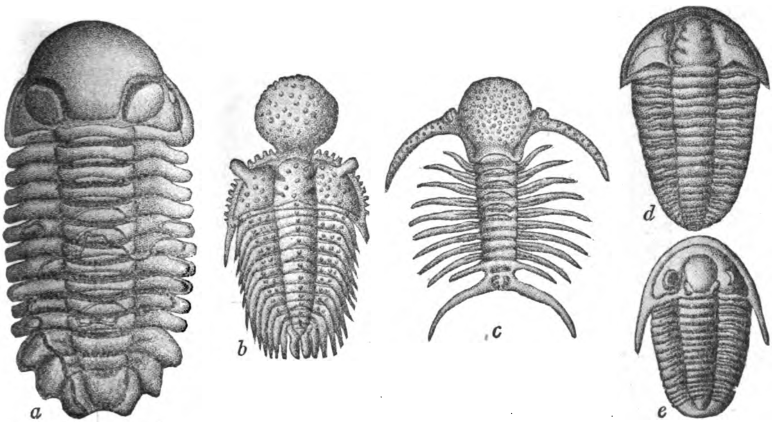



Fig. 353. SILURIAN TRILOBITES: *a*, *Sphærexochus mirus* Bey., dorsal view; *b*, *Staurocephalus murchisoni* Barr, dorsal view, showing the peculiar globular anterior prolongation of the head; *c*, *Deiphon forbesi* Barr, dorsal view of a peculiar trilobite having the pleural lobes much reduced; *d*, *Calymene niagarensis* Hall, dorsal view of one of the commonest Silurian trilobites; *e*, *Cyphaspis christyi* Hall, dorsal view.

offset the disappearance of old ones, and the class, though still important, had already begun its decline. The highest forms were, however, equal, if not superior, to any that preceded.

*Sponges* flourished. There was a prolific field of them in western Tennessee, where the conditions were not only congenial to their growth, but favorable for their preservation. *Graptolites* had lost the importance they had in Ordovician times, and by the end of the period neared extinction. *Sea-worms* are recorded through their jaws, tracks, and burrows, and by the calcareous tubes which some of them secreted.

In the earlier and mid-Silurian deposits few relics of *fishes* have been found, and these few are very imperfect; but in the upper part of the system their remains are not rare.

Knowledge of Silurian marine plant life is meager. While it must have been abundant theoretically, only obscure markings have been found, and their interpretation is more or less doubtful.

**Late Silurian fauna.** Following the luxuriant life of the mid-Silurian epoch, there came, in North America at least, a notable decline, due to the withdrawal of the epicontinental waters from the

Fig. 354. *Receptaculites oweni* Hall; "lead coral" or "sunflower"; original 9¼ inches in diameter.

larger part of the interior, and to the conversion of the remainder into an excessively salt sea, in the deposits of which few fossils are found. At the very close of the period there was in the Salina basin a gradual return of conditions hospitable to life. The fauna of these late Silurian beds is limited, and radically unlike that which preceded. Most of the familiar marine types are absent from the later fauna, and its signal feature is an abundance of *arthropods* (p. 686) of types barely represented before. The most characteristic of these were the great *Eurypterus* and the still more gigantic *Pterygotus* (Fig. 355, *a* and *b*). The former reached a length of a foot and a half or more, and in the next period the latter attained a length of over six

feet. These giants among their kind were aquatic, but whether inhabitants of salt or fresh water is not certain.

Mollusks, crinoids, corals, and similar marine forms are almost entirely absent from the fauna of the Waterlime. The few brachiopods found are usually pauperitic, as though they lived in uncongenial conditions.

It was at this time that the earliest known *scorpions*, kin of the eurypterids, appeared both in America and Europe. The European

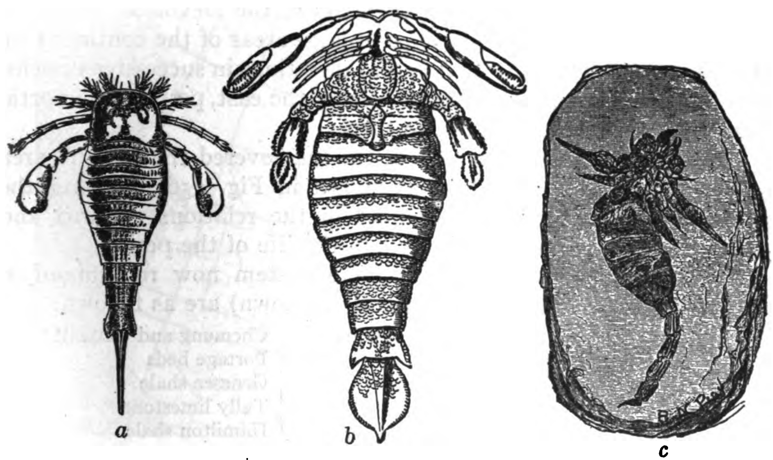



Fig. 355. *Arthropods, other than Trilobites: a, Eurypterus fischeri* Eich.; *b, Pterygotus anglicus* Agass.; *c, Palæophonus caledonicus* Hunter.

forms have been thought to be land species, though this has been questioned. The stings and poison glands have been identified, and the significant name, *Palæophonus*, "ancient murderer," applied in consequence (Fig. 355, *c*). The American species have been thought to be aquatic.

The presence of *fishes* emphasizes the peculiarities of this fauna. Except for their occurrence at a few points in the Rocky Mountains in the Ordovician, fish remains have not been found in America until this stage. In Europe a few fishes appear somewhat earlier, but nearly all fish remains of the period yet found are in the uppermost horizons of the Silurian, or in deposits that form the transition to the Devonian, where they are associated with eurypterids, land plants, and marine invertebrates.

# CHAPTER XVIII

## THE DEVONIAN PERIOD

### FORMATIONS AND PHYSICAL HISTORY

The most important physical events of the Devonian period in North America were the invasions of large areas of the continent by the sea, which came in from different directions in successive epochs. The invasions appear to have been from the east, perhaps the north, the south, and the northwest, in turn.

Early in the Devonian period, the sea covered the present area of land to some such extent as shown in Fig. 356. During the period, there were notable changes in the relations of land and water, with corresponding changes in the life of the period.

The subdivisions of the Devonian system now recognized in New York (where the Devonian is best known) are as follows:

| | | | |
|---|---|---|---|
| Devonian | Upper Devonian | Chautauquan | Chemung and Catskill |
| | | Senecan | Portage beds |
| | | | Genesee shale |
| | | | Tully limestone |
| | Middle Devonian | Erian | Hamilton shale |
| | | | Marcellus shale |
| | | Ulsterian | Onondaga limestone |
| | | | Schoharie grit |
| | | | Esopus grit |
| | Lower Devonian | Oriskanian | Oriskany beds |
| | | Helderbergian | Kingston beds |
| | | | Becraft limestone |
| | | | New Scotland beds |
| | | | Coeymans limestone |

The subdivisions of the last two columns do not fit regions remote from New York, though the names, Helderberg (or Helderbergian), Oriskany, Onondaga (Corniferous), Hamilton, Portage, and Chemung, have rather wide application.

### *Devonian of the East*

**The Lower Devonian.** The known *Helderbergian series*, largely limestone, is known in (1) the northeast, (2) the Appalachian belt,

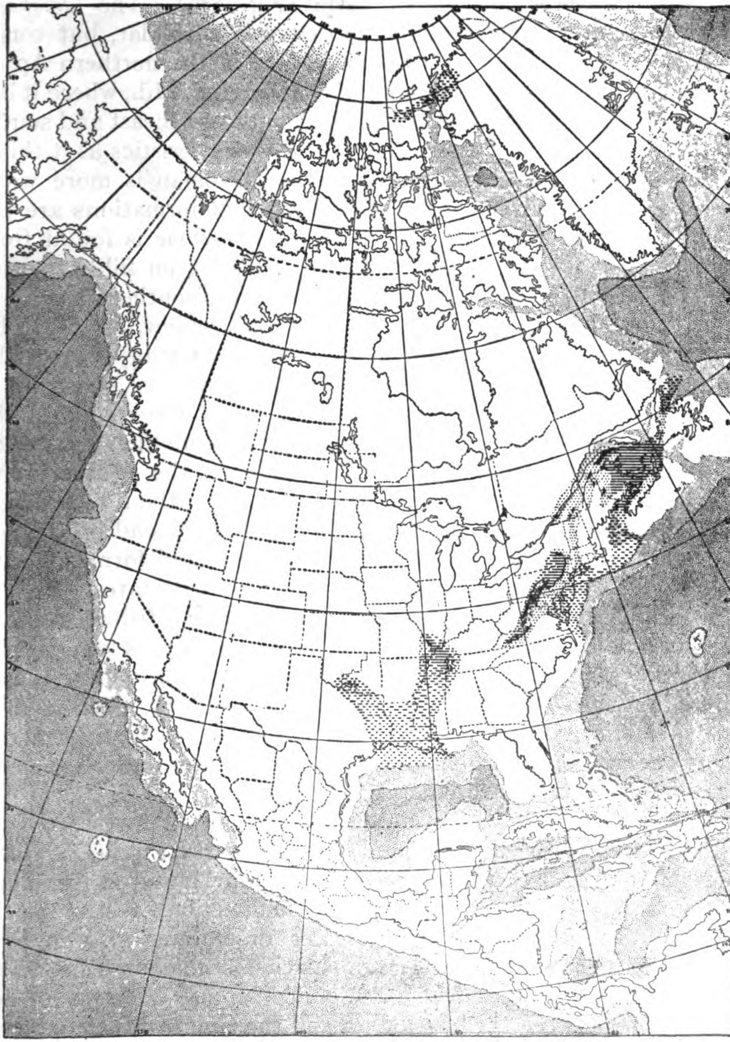


Fig. 356. Map of North America, showing the outcrops of the Helderberg formation and the general relations of land and water during the Helderberg epoch. The conventions are the same as in the earlier maps of the series.

and (3) the lower Mississippi basin (Fig. 356). The *Oriskany formation*, chiefly sandstone in the east, has a similar, but somewhat wider, distribution. It is best known in the northern Appalachian region. From the vicinity of Cumberland, Md., where it has a thickness of a few hundred feet, it thins to the northeast and southwest, and loses its most distinctive faunal characteristics as it thins.

**The Middle Devonian.** The Middle Devonian is more widespread than the Lower and its most important formations are the Onondaga and Hamilton. The *Onondaga limestone* is found from New York to the Mississippi (Fig. 357), resting on Silurian beds with little evidence of unconformity. The epicontinental sea in which it was formed was relatively clear and shallow, as shown by the composition of the rock and its fossils. In many places the limestone is rich in coral, and locally the coral-reef structure is shown perfectly. This is true, for example, at the rapids of the Ohio near Louisville. The formation is rarely more than 100 to 200 feet. In northern New England and Canada, the equivalent of this formation has a distribution similar to that of the Lower Devonian. It occurs also on the west side of the south end of Hudson Bay, and the beds here may have been connected formerly with equivalent formations in the interior of the United States.

Following the Onondagan epoch of clear seas, conditions changed so as to give origin to deposits of mud in many places where limestone had been forming. These mud beds, now consolidated, constitute the *Marcellus* and *Hamilton* formations of New York (p. 402). In the interior, where there is more limestone, the equivalents of the two formations are commonly grouped together under the name Hamilton, or given local names.

Considerable areas in the southern and in the northwestern parts of the Mississippi basin which had been land earlier, appear to have been submerged at this time (Fig. 358), for the Hamilton formation appears to overlap its predecessor in these directions, resting on the Silurian. The spread of the sea at this time seems also to have submerged areas in the southern Appalachians which had been land since the close of the Ordovician. Connection may have been made at this time between the interior sea and the Gulf of Mexico, allowing shallow-water species of animals to migrate from the south into the Mississippi basin.

The conditions for the origin of the Hamilton shales would seem to be met if the surrounding lands (Appalachia and lands north of

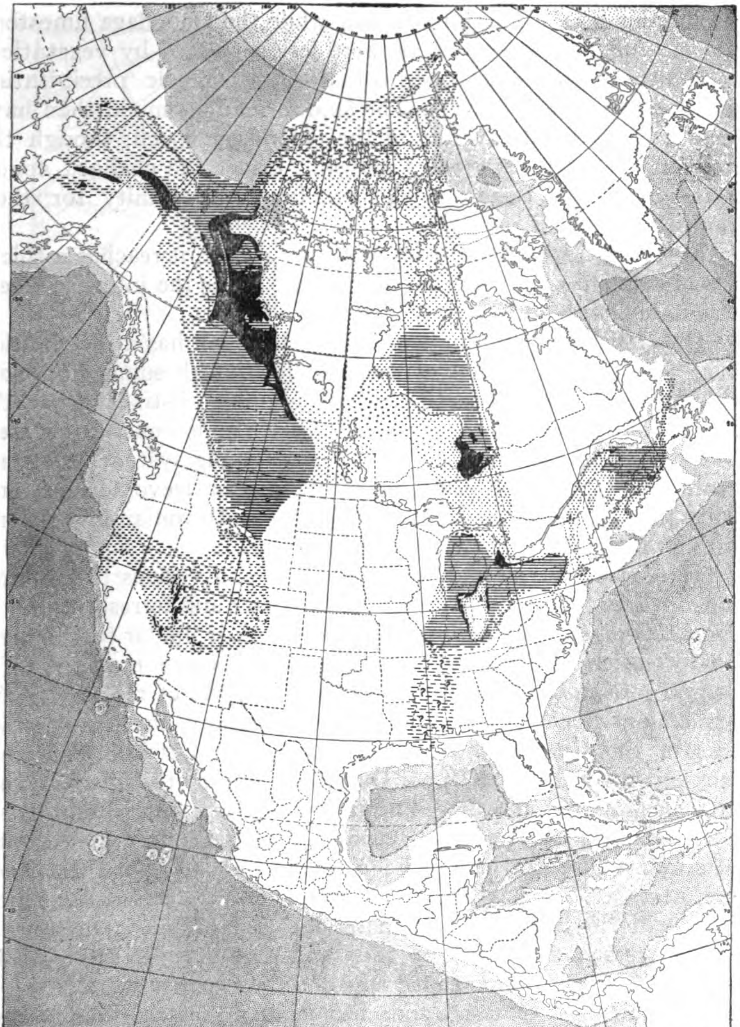


Fig. 357. Map of North America, showing the outcrops of the Onondaga formation, and the general relations of land and water during the Onondaga epoch. The Devonian at the northwest is not all Onondagan. Note the interrogation marks in the lower Mississippi valley.

the interior sea), after standing low while the Onondaga limestone was making, were elevated, or were less protected by vegetation, or subjected to more concentrated or spasmodic precipitation during the Hamilton epoch. The land formations might then have been undergoing decay during the Onondaga epoch, though the products of decay were not removed. Under the changed conditions postulated, there would have been opportunity for their transportation and deposition.

In the east, where the series is mainly clastic, it reaches a thickness of 1,500 to 5,000 feet (Pennsylvania); but in the interior, where it contains more limestone, it is much thinner.

**The Upper Devonian.** The Upper Devonian has a distribution (Fig. 359) similar to that of the Middle, though somewhat more widespread. The Upper Devonian is more distinct from the Middle than the Middle is from the Lower, and is somewhat closely connected with the lower part of the succeeding system.[1] An uncomformity appears at the base of the Upper Devonian in some places, and in others the series overlaps other Devonian formations, resting on the Ordovician.

The *Senecan series* of New York consists of various thin formations (p. 402), chiefly clastic, of shallow-water and terrestrial origin. The *Chemung formation* of western New York is similar to the Senecan formation, though more sandy, or even conglomeratic. The *Catskill formation* of the Catskill region consists of red shales and sandstones, which appear to be, in a general way, the time-equivalents of the Chemung. In some places the Catskill beds may represent more than the Upper Devonian, and in others less. They are poor in fossils, and those known are partly, if not wholly, fresh- and brackish-water forms. Hence it is inferred that the Catskill region was so far shut off from the ocean as not to afford the conditions necessary for marine life. Redness characterizes many formations made in inclosed or partially inclosed basins. Outside the Catskill region local beds of red sandstone suggest that similar conditions of deposition existed now and then farther west.

The thickness of the Upper Devonian in central and western New York approaches 4,000 feet, and is even more in Pennsylvania and Maryland. In Ohio the equivalent series (Black, or Ohio

[1] Ulrich has recently proposed grouping the Upper Devonian with the lower part of the Mississippian, as a new system, under the name of Waverlyan. Bull. Geol. Soc. Am., Vol. XXII.

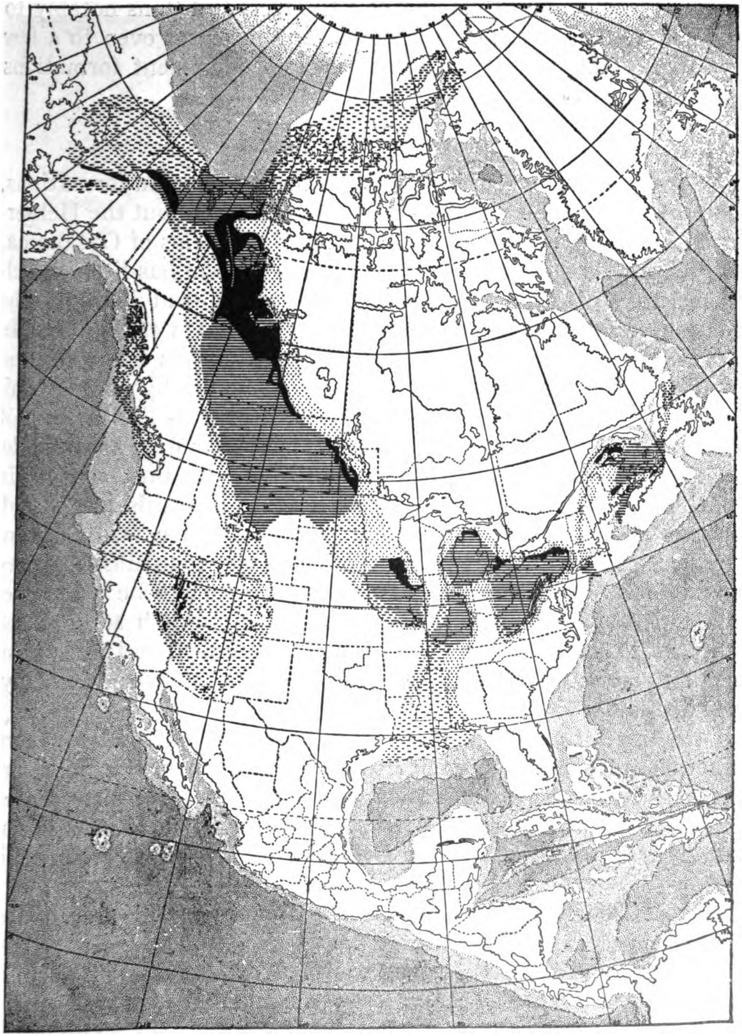


Fig. 358. Map of North America showing the outcrops of the Hamilton formation and the general relations of land and water during the Hamilton epoch. The black area at the north probably includes Lower and Upper Devonian as well as Middle. Compare Figs. 356 and 357. The conventions are the same as in earlier maps.

shale) has a maximum thickness of 2,600 feet, and thins notably to the north and west, to a few hundred, and in places even to a few score feet. Different names are applied to equivalent formations in various localities.

## *Devonian of the West*

Most of the Great Plains region is without Devonian formations, so far as known, and so is inferred to have been land; but the Helderberg formation is present in the Arbuckle Mountains of Oklahoma, and probably in southwestern Texas. The system has little development in the Rocky Mountains, but is widespread between the Rockies and the Sierras, though its outcrops are not extensive. In some places, as about Globe, Arizona, the system is much faulted and affected by igneous rock;[1] in others it is bounded by unconformities, both below and above, while in still others its limits are not defined sharply. Where subdivisions of the system have been made, they are not correlated with those of the east. In the Great Basin region, both Onondagan and Hamilton types of fossils are found. Their testimony is to the effect that the basin region was not connected with the eastern interior sea in such a way as to allow the free intermigration of marine life. The system is said to be 8,000 feet thick in parts of Nevada, and 2,400 feet in the Wasatch Mountains; but in the Yellowstone Park, it is only 160 feet thick, and not divisible into distinct formations. In the western interior generally, limestone is the dominant formation.

Devonian formations are known in both northern and southern California, and may be present in many places where the rocks are metamorphosed past identification. The system also is represented in widely separated parts of Alaska. The Devonian faunas of the coastal region, like those of the Great Basin, are Eurasian in their affinities.

**Middle Devonian in the northwest.** A considerable area of Devonian which has sometimes been called Hamilton is found in the basin of the Mackenzie River and south to Manitoba. The arm of the sea in which these Devonian beds accumulated appears to have extended as far south as northern Missouri (Fig. 358). The fossils of this northwestern Devonian are different from those of the Hamilton fauna east of the Mississippi, and if the beds of the two

[1] Ransome, Professional Paper No. 12, and Bisbee folio, U. S. Geol. Surv., pp. 39–46.

Fig. 359. Map of North America, showing the outcrops of the Upper Devonian formations, and the general relations of land and water in late Devonian time. The conventions are the same as in earlier maps (see p. 347). (See note under Fig. 358 concerning the Devonian in the northwest. Note also the interrogation marks in the lower Mississippi basin.)

regions were contemporaneous, they were probably deposited in waters which were not connected (Fig. 358). Toward the end of the Hamilton epoch, the barrier which separated their waters seems to have been removed sufficiently to allow the waters and the life on opposite sides to mingle freely (Fig. 359).

## *General Considerations*

**Outcrops.** While the Devonian system is widely distributed in North America, it does not appear at the surface in large areas. The reasons are substantially the same as those for the limited exposures of earlier systems. The removal of Devonian from areas it once covered is oddly shown near Chicago, where a small remnant of Devonian sediment has been found in a fissure in the Niagara limestone, as shown in Fig. 360. The limestone was apparently fissured before the Devonian sediments were deposited upon it. Portions of the sediments fell into an open fissure, carrying with them distinctive fossils (fish teeth). In this protected position, the fossils escaped removal.

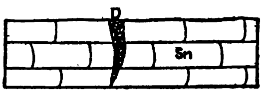



Fig. 360. Figure illustrating the occurrence of remnants of Devonian material in fissures in Niagara limestone, near Elmhurst (Cook Co.), Illinois.

**Igneous rocks.** Igneous rocks have little representation in most parts of the system in North America, but in Nova Scotia, New Brunswick, and Maine, and at some points in the west, there are igneous rocks which appear to be of this age. In many places in the west, Devonian strata have been affected by dikes and intrusions of later times.

**Close.** The general quiet which had prevailed during the period seems not to have ended at its close. Only in the eastern part of the continent, so far as now known, in Maine, Nova Scotia, New Brunswick, and the adjacent region to the north were Devonian strata notably disturbed at the close of the period. Elsewhere the formations of the younger system rest on those of the older without stratigraphic break.

## *Economic Products*

The Upper Devonian is the chief source of *oil and gas* in western Pennsylvania and southwestern New York, and is one of the sources in West Virginia. The Middle Devonian is oil-producing in Ontario. Within the regions of their occurrence, oil and gas are more likely to be found under low anticlines than in other positions,

apparently for the reason that anticlines furnish an inverted basin capable of holding these substances against the pressure of the


Fig. 361. Section showing the relations of the Devonian and other Paleozoic systems in the vicinity of Loudon, Tenn. Є = Cambrian; *O* = Ordovician; *S* = Silurian; *D* = Devonian; *au* = age unknown. Length of section, about 7 miles. (Keith, U. S. Geol. Surv.)

heavier subterranean water which tends to force them to the surface. In all cases it appears that there must be impervious beds above to prevent the escape upward of the oil and gas.

The Devonian of central Tennessee is the horizon of black *phosphates*, which are of importance commercially.[1]

### *Foreign Devonian*

**Europe.** At the close of the Silurian there seem to have been more considerable geographic changes in Europe than in America, for the Devonian system there is more commonly unconformable on its base. During the progress of the period, Europe was progressively submerged, for the Middle and Upper Devonian formations are more widespread than the Lower (Fig. 362).

In the *British Isles* the Devonian system has two phases. The first is found in the area which gave the system its name (Devonshire). The system here is thick and of marine origin. Igneous rocks are associated with the sedimentary, and the system has valuable ore-bearing veins, as in Devon and Cornwall.

The second phase of the Devonian is the *Old Red Sandstone,* widely distributed in Great Britain and Ireland and found at some points on the continent. Concerning the history of this sandstone there has been much difference of opinion, but it is believed to have been deposited in a series of inland lakes or seas, the waters of which were fresh or brackish. Since species of marine fossils occur at some horizons, the sea had access to the basins at times. It is not improbable that some parts of this singular sandstone are of subaërial, rather than subaqueous, origin. The Old Red Sandstone has some features like those of the Catskill formation of America. In the British Isles, the Old Red Sandstone has great thickness and includes much igneous rock.

[1] Columbia (Tenn.) folio, U. S. Geol. Surv.

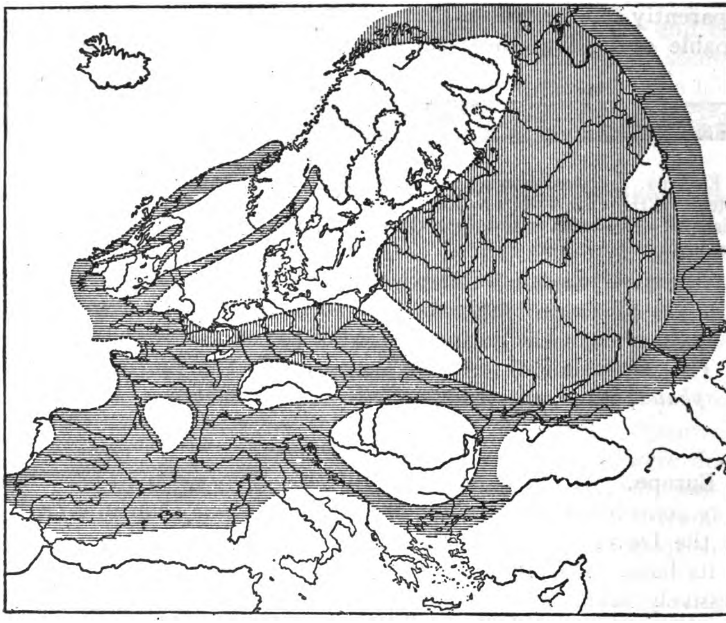


Fig. 362. Sketch map of Europe during the Devonian. The horizontal lines represent the Lower Devonian; the vertical lines mark the additional areas where the Middle Devonian occurs. (After De Lapparent.)

In the *Devonian of Germany* much igneous rock is interbedded with the sedimentary. The igneous rock occurs in many separate beds, showing that there were many periods of igneous activity separated by intervals of quiet. In not a few places, especially where the sedimentary rocks have been invaded by igneous rocks, mineral veins have been developed, and from them large quantities of iron, tin, copper, and other metals have been obtained.

The *Devonian of Russia* is made up of beds of arenaceous and calcareous rocks, the former containing fossils related to those of the Old Red Sandstone, the latter containing fossils of a marine fauna. The Lower Devonian appears to be wanting in much of Russia, and the Middle and Upper parts of the system are in most places unconformable on subjacent formations.

**Other continents.** The Devonian system has wide distribution in Siberia and China, and is known at many points in southern Asia. It occurs in North and South Africa, in New South Wales,

and Victoria and New Zealand, and the Lower Devonian especially has considerable development in South America.

### *Climate*

Conclusive evidence of great diversity of climate, or of variations of climate during the period, are not at hand. The Old Red Sandstone and the Catskill formation perhaps point to aridity, but this can hardly be affirmed. In formations thought to be Devonian, evidences of glaciation have been reported from South Africa,[1] but the evidence is perhaps not conclusive.

## LIFE

### *The Marine Faunas*

At the beginning of the period shallow-water faunas were restricted to limited bodies of water about the continental borders. The life of these several bodies of water developed differently. The early Devonian life consisted of the expansions of these provincial faunas. When in the early Devonian the sea invaded the land from these different embayments, the advance from each carried its own somewhat peculiar fauna toward the interior. The faunas invaded the continent more or less simultaneously, but they reached the interior more or less successively. The following faunas have been recognized: (1) the Helderberg, (2) the Oriskany, (3) the Onondaga (Corniferous), (4) the Southern Hamilton, (5) the Northwestern Hamilton fauna, and (6) the late Devonian fauna. They reached the interior in the order named. As each in turn came in contact with the preceding fauna, there was a mingling of the two, resulting in the destruction of some species and the modification of others. A new, composite fauna developed from the survivors.

**Helderberg fauna.** The Helderberg fauna seems to have developed from the late Silurian fauna in the embayment at the mouth of the St. Lawrence and on the border of the adjacent continental shelf, and perhaps also on the border of southern Europe. It appears to have found its way into the Appalachian valley-trough, and thence to have spread westward and northward, but not beyond the eastern part of the great interior region. Perhaps it reached the interior also from embayments on the southern coast. The fauna had much in common with the contemporaneous fauna (Hercynian) of southern Europe, but both differed markedly from

[1] Schwarz, Jour. Geol., Vol. XIV, p. 683, and David, Q. J. G. S., Vol. XLIII.

the early Devonian faunas of the northern latitudes of Europe and America.

The main features of the Helderberg fauna were great numbers of *mollusks* and *brachiopods*, an erratic tendency of the *trilobites*,

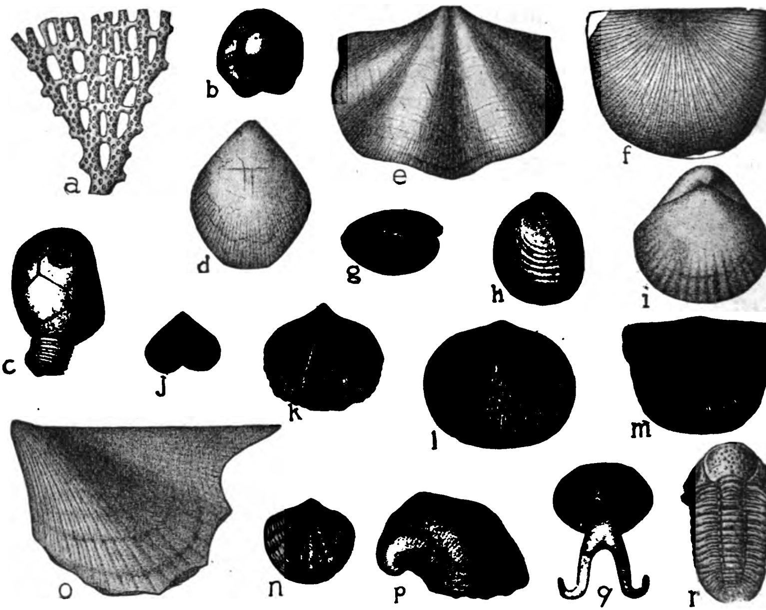



Fig. 363. HELDERBERGIAN FOSSILS: *a*, *Polypora lilæa* (Hall), a fenestelloid bryozoan representative of a group which was of great importance later; *b*, *Michelinia lenticularis* Hall, the earliest member of a genus of corals which became abundant in later Devonian faunas; *c*, *Lepocrinites gebhardii* Con., one of the last representatives of the cystids. *d-n*, Brachiopods: *d*, *Rensselæria æquiradiata* (Con.), a representative of a genus characteristic of the Lower Devonian; *e*, *Spirifer macropleurus* (Con.), a species closely related to the Silurian species of the genus; *f*, *Strophonella punctulifera* (Con.); *g*, *Schizophoria multistriata* (Hall); *h*, *Uncinulus mutabilis* (Hall), a representative of a genus which had its greatest development in the Helderbergian fauna; *i*, *Gypidula galeata* (Dal.), one of the most characteristic species of the Lower Helderberg; *j*, *Bilobites varicus* (Con.), a type of orthid characteristic of the Silurian and Helderbergian; *k*, *Eatonia medialis* (Van.), a representative of a genus most characteristic of the Lower Devonian; *l*, *Rhipidomella oblata* (Hall); *m*, *Leptæna rhomboidalis* Wilck., a species which ranges from the Ordovician to the Mississippian; *n*, *Atrypina imbricata* (Hall), a lingering Silurian type; *o*, *Actinopteria textilis* (Hall), a winged pelecypod of a type which had great expansion in the Devonian; *p*, *Platyceras gibbosum* Hall, a capulid gastropod; *q*, *Dicranurus hamatus* (Con.), a trilobite whose closest relative occurs in Barrande's Etage G, in Bohemia; *r*, *Phacops logani* Hall, a representative of a genus of trilobites which had its greatest development in the Devonian.

a paucity of *crinoids* and *corals*, and a notable absence of *fishes*. Fig. 363 shows some of the characteristic forms.

**Oriskany fauna.** The Oriskany fauna was a sand-loving fauna which followed the Helderberg into the interior apparently by a similar route. Its place of origin is not known with certainty, but its habitat was probably on the Atlantic coast. It was bound by many ties to the Helderberg fauna, but contained distinctive features, implying a partly separate origin. On the whole, this fauna was essentially an assemblage of well-fed mollusks and molluscoids, with but a sprinkling of other types. Brachiopods were, on the whole, the most distinctive forms.

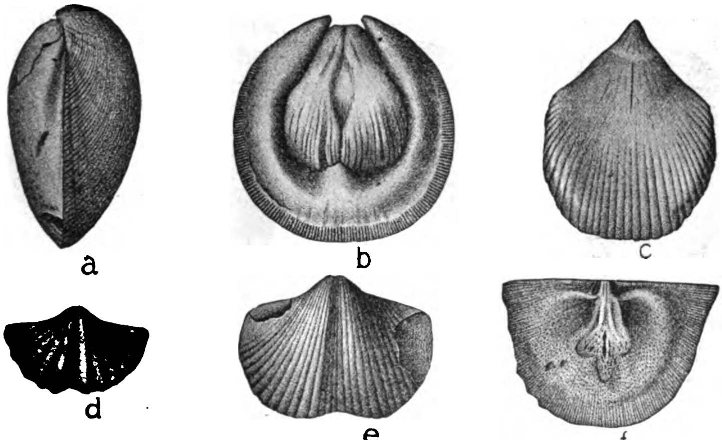



Fig. 364. Oriskany Fossils. Brachiopods: *a*, *Rensselæria ovoides* (Eaton); a representative of a genus restricted to the Helderbergian and Oriskany (see Fig. 363, *d*); *b*, *Hipparionyx proximus* Van., one of the most characteristic fossils of the arenaceous Oriskany beds; *c*, *Camarotœchia barrandei* (Hall), one of the large rhynchonelloid shells of the Oriskany; *d*, *Spirifer murchisoni* Castel, and *e*, *S. arenosus* (Con.), two of the most characteristic Oriskany species, the first occurring throughout the fauna, the second mainly in the fauna of the arenaceous beds; *f*, *Stropheodonta magnifica* Hall, a species which sometimes grew to be four or five inches across. The genus has its great expansion in the Devonian. The figures are much smaller than the fossils, the largest shells being 4 to 5 inches across. The large size of the Oriskany brachiopods may be appreciated by comparison with Fig. 363, the brachiopods of which are reduced to the same extent as those of this Fig.

**Onondaga fauna.** The Onondaga fauna was distinguished from the preceding by hosts of *marine fishes* of divergent types. From this time on fishes were abundant in the epicontinental waters of America and Europe, and doubtless ranged widely over the seas.

A feature of the Onondaga formation consists of thin layers ("bone-beds") made up almost wholly of their plates (scales), teeth, spines, etc. Among the fish were (1) *arthrodirans* whose necks were so joined to their bodies as to give their heads vertical motion, a rare feature among fishes; (2) *sharks* of various types; and (3) *ganoids* with cartilaginous skeletons and bony scales, in contrast with the modern *teleosts* which have bony skeletons and membranous scales. These fishes seem to have been more fully clothed with spines and defensive armor than their descendants. Compared with existing species, they were doubtless heavy, clumsy, and sluggish. From the degree of development already attained, it may be inferred that

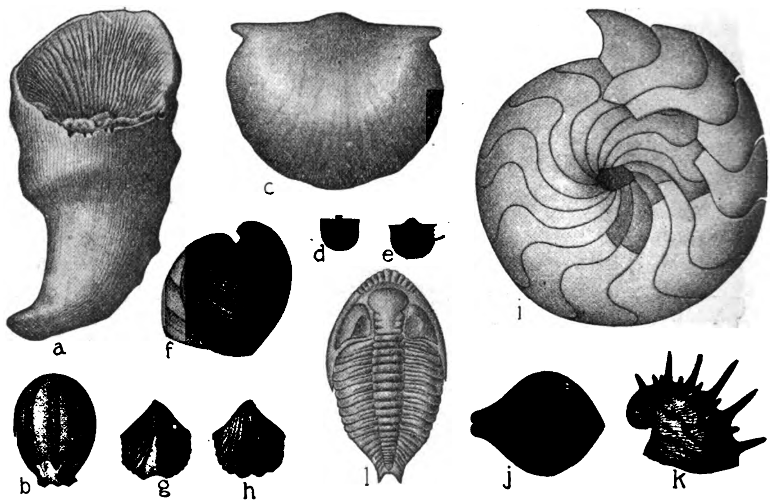



Fig. 365. Onondagan Fossils: *a*, *Zaphrentis ponderosa* Hall, a medium-sized, simple horn coral; *b*, *Nucleocrinus verneuili* (Troost), a blastoid abundant in one layer of the Onondagan limestone in the Ohio Valley; *c-h*, brachiopods: *c*, *Stropheodonta concava* Hall; *d* and *e*, *Productella spinulicosta* Hall, an early representative of a genus which became abundant in the Upper Devonian, and gave rise to the typical *Productus* of the Mississippian and Pennsylvanian faunas; *f*, *Spirifer acuminatus* (Con.), a characteristic Onondagan brachiopod; *g* and *h*, *Crytina hamiltonensis* Hall, two views of a species having a wide geographic distribution and a great geologic range in the Middle and Upper Devonian; *i*, *Tornoceras mithrax* (Hall), the first goniatite in America. The goniatites are distinguished from earlier cephalopods by their lobed sutures; *j*, *Conocardium trigonale* Hall, a dorsal view of a common Onondagan pelecypod; *k*, *Platyceras dumosum* Con., a capulid gastropod with large hollow spines; *l*, *Odontocephalus ægeria* (Hall), a trilobite showing ornamentation of the border of the head and tail.

their ancestors had been living for a long time in the region where they originated, probably somewhere in the north.

Another significant feature of the Onondaga fauna is the profusion of *corals*. From the rapids of the Ohio at Louisville, more than 200 species have been collected, embracing both the simple cup form (*a*, Fig. 365) and the compound type. Some of the cup corals attained a length of 18 inches and a diameter of 3, but the range in size was great. The reef-building habit attained greater development than in Silurian times, the reef at the rapids of the Ohio being the most famous example. *Crinoids* were rather few, but they do not appear to have lost their vitality, for they were abundant later. Large *Brachiopods* and *cephalopods* were plentiful. It will be remembered that in the primitive types of the cephalopods, the septa of the shells were plane or symmetrically curved, and that their juncture with the outer shell was a simple curve. In the Onondaga epoch, one form had septa which were bent abruptly, and suture lines which were lobed (*i*, Fig. 365). This was the first notable step in a remarkable series of crumplings of the septa which developed later. *Gastropods* similar to those of the earlier Devonian faunas were present, and the spines of the shells had now become pronounced in one group of them, perhaps signifying the necessity of defense against the abundant fishes and cephalopods. *Pelecypods* were abundant, many of them descended, no doubt, from Helderberg and Oriskany ancestors. *Trilobites* were present in more than half a hundred species, some of them being highly ornamented.

It seems clear that some of the species were descendants from the Helderberg and Oriskany faunas. Other prominent elements of the fauna, particularly the fish, cephalopods, and corals, seem, with equal clearness, to have come in from some other source. The striking features of the fauna seem to be explained by supposing that there was a generating tract to the north,[1] either on the American or European continent, and that from this source migration into the interior sea of North America took place as the waters from the north extended themselves over the continent. As the result of the invasion, some part of the Oriskany fauna which already occupied the interior sea was driven out or destroyed, while the rest intermingled with the northern invaders.

[1] This conclusion is not universally accepted. See Schuchert, Bull. Geol. Soc. Amer., Vol. XX.

**Southern Hamilton fauna.** At the beginning of the Hamilton epoch, there was a great influx of muddy material into the eastern part of the interior sea, while farther west the formation of limestone continued as before. At about this time, it appears that a fauna whose forbears lived in South America entered the interior sea, and, joining the resident Onondaga fauna, gave origin to the Southern Hamilton fauna. The transformation was not so radical as that which attended the invasion which gave rise to the Onondaga fauna, because the invaders were then the master type.

*Fishes* were a conspicuous part of the new fauna. The *arthrodirans* reached their climax, and some of the species were among the largest fish ever known. Some of them had an estimated length of 20 feet, and had strong mandibles 2 feet long (Fig. 366) which,

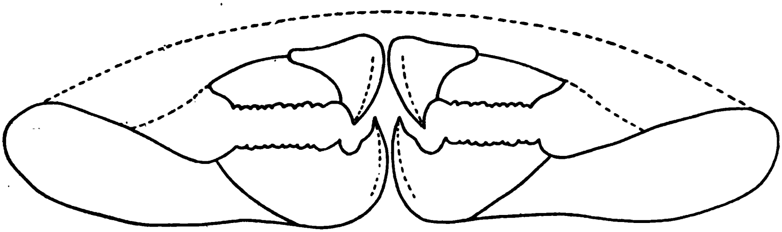


Fig. 366. Diagrammatic front view of the dentition of *Dinichthys herzeri*, Huron Shales, Delaware, O. (After Newberry.)

in lieu of teeth, had cutting edges that closed, shears-like, after the fashion of the mandibles of turtles. The front part of the body was encased in heavy plates. Some of the fin-spines of sharks were a foot long. In both groups of fish the devices of warfare make up nearly the whole record, and this doubtless implies the conditions in which the vertebrates lived.

*Polyps* were affected adversely by the muddy waters. *Crinoids* were abundant locally, certain beds of limestone being composed largely of their remains. *Brachiopods* reached their climax at about this time. Among them, the *spirifers* attained their greatest extension of hinge-line (*j*, Fig. 367) a feature characteristic of the Hamilton epoch. The muddy bottoms favored *mollusks*. *Goniatites* increased in numbers and size (Fig. 367, *o*), and *pelecypods* still more, the number of known species approaching 200. At this time appeared the first known *barnacles* of the modern sessile type. In losing its pedicel and in fixing itself immovably on other objects, it became degenerate, but it found a lowly place to which it has

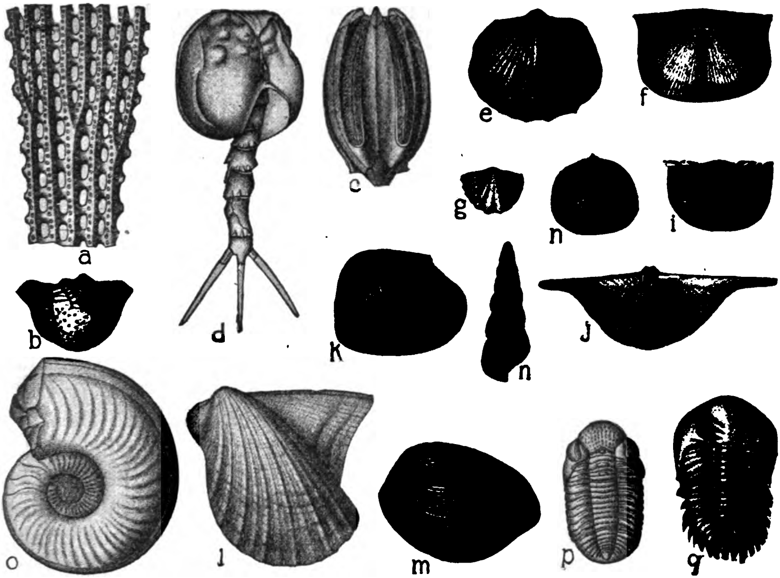



Fig. 367. REPRESENTATIVE HAMILTON FOSSILS: *a, Fenestella emaciata* Hall, a type of bryozoan common in the Middle Devonian; *b, Arthracantha punctobrachiata* Williams, one of a genus of crinoids restricted to the Middle and Upper Devonian; *c, Eleutherocrinus cassedayi* S. and Y., a peculiar, irregular blastoid; during life it probably rested upon one side on the sea bottom. *d, Echinocaris punctata* (Hall), a crustacean more highly organized than the trilobites. *e-j*, brachiopods: *e, Tropidoleptus carinatus* (Con.); *f* and *i, Chonetes coronatus* (Con.); *g, Vitulina pustulosa* Hall; *h, Rhipidomella vanuxemi* Hall, a representative of the orthids, which had great development in the Devonian; *j, Spirifer pennatus* (Atw.), one of the long-hinge-lined spirifers most conspicuous in the Middle and Upper Devonian; *k, l,* and *m*, pelecypods: *k, Cypricardella bellistriatus* (Con.); *l, Pterinea flabella* (Con.); *m, Palæoneile constricta* (Con.); three pelecypods common in the Hamilton. *n, Loxonema hamiltoniæ* Hall, a gastropod common in this epoch; *o, Goniatites vanuxemi* (Hall), a characteristic cephalopod of this fauna; *p, Phacops rana* (Greene) the most common trilobite of the Hamilton, and representative of a genus which has its greatest expansion in the Devonian; *q, Cryphæus boothi* Greene, one of the last of the dalmanites.

hung with wonderful persistence, not unlike the debased human class which it has come to typify.

**Northwestern Hamilton fauna.** While the preceding fauna was developing in the eastern interior sea, another fauna was evolving on somewhat different lines in the northwestern sea which overspread a large part of the northwestern interior (Fig. 358). For a time this northwest sea was not in communication with the sea in

which the Southern Hamilton fauna lived (Fig. 358), but the intervening barrier disappeared finally, and the northwestern fauna overran the territory already occupied by the Southern Hamilton fauna (Fig. 359). This northwestern fauna was closely allied to the Devonian fauna of eastern and central Europe. The southward extension of this great arm of the sea took place late in the period, for the strata bearing its peculiar life lie on pre-Devonian formations in Missouri, Iowa, and Minnesota, and overlie the Hamilton in the more eastern region.

**Later Devonian (Chemung) fauna.** The commingling and conflict which attended the invasion of the eastern and southern interior sea by the European and Eurasian faunas may be regarded as the controlling event in the evolution of the Upper Devonian fauna. As in the case of the Onondaga invasion, the northern immigrants were the more virile, and gave character to the composite fauna that arose later from the extinction of the weaker species, and the adaptation of the survivors to one another. There were three dominant factors in this development, (1) the resident Southern Hamilton species, (2) the invading European and Eurasian species, and (3) the shallow and rather turbid waters in which these species met and merged. The last of these factors showed itself in a notable rarity of *corals*. The *brachiopods* best express the outcome of the commingling of resident and immigrant species. Among them, as in the whole fauna, there was an indigenous set of species developed from the preceding residents, and an exotic set derived from the immigrants and bearing North-European characters. The latter was the more conspicuous. Among the *mollusks*, however, the case was the reverse, and the majority seem to have been descendants of the resident bivalves.

**Devonian fauna in the Great Basin area.** In the Great Basin region of the west, a large area seems to have been occupied continuously by the sea from about the beginning of Middle Devonian time to the later portion of the Carboniferous period. It seems to have been measurably free from both the physical and the biological changes which gave such diversity to the eastern provinces. Its fauna had a slow, continuous evolution, favored, from time to time, it would appear, by accessions from the north, and perhaps from other sources as well. None of the distinctive South American forms appeared in it, nor any of the peculiar Helderberg or Oriskany species. It is inferred, therefore, that it was shut off from the

eastern and southern interior throughout the whole Devonian period. On the other hand, a notable number of species were common to it and to the northwestern province.

### *Life of Land Waters*

Certain Devonian formations, such as the "Old Red Sandstone" and the Catskill formation, appear to be composed of deposits laid down in more or less local lodgment basins that were progressively filled by land-wash and fresh-water sediments. These basins appear to have been the home of a fresh- or brackish-water fauna, among which fishes, crustaceans, and ostracoderms were conspicuous. Perhaps the geological record presents no more suggestive combination of ancient life. The type of the fauna was foreshadowed by the eurypterids and fishes, or fish-like forms of the late Silurian; but the record of that time is less perfect than that of the late Devonian.

The center of interest in this fauna is found in the *ostracoderms* (Figs. 368 and 369), a class of animals between arthropods and

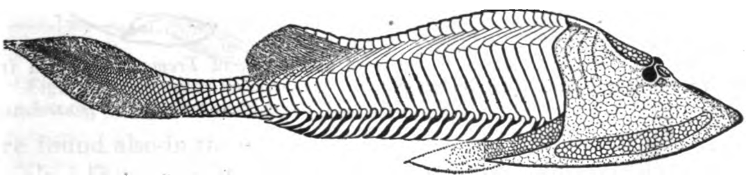


Fig. 368. Restoration of *Cephclaspis*, seen from the side. (After Patten.)

vertebrates. Their chief interest lies in their suggestion that vertebrates sprang from arthropods. The ostracoderms bear external resemblances, in the head and trunk, to trilobites and king-crabs, while some of them have caudal fins and fish-like bodies. They were formerly classed as fishes, but no vertebræ have been found, or appendages or jaws of the vertebrate type. Ostracoderms probably formed the climax and almost the end of their own strange race, for they practically disappeared with this period. This is not surprising in view of the development of powerful fishes, for the ostracoderms were obviously not a masterful race. Besides being small, they were clumsy, and their mouth-parts were weak. They probably plowed the soft bottoms of the sluggish waters, half buried in the mud, above which little beside their peculiarly placed eyes and the backs of the plated bucklers were habitually exposed.

Another class of strange organisms related to the fishes, but not

true fish, was represented by the singular little *Palæospondylus* (Fig. 370), which represents the vertebrate idea in great simplicity.

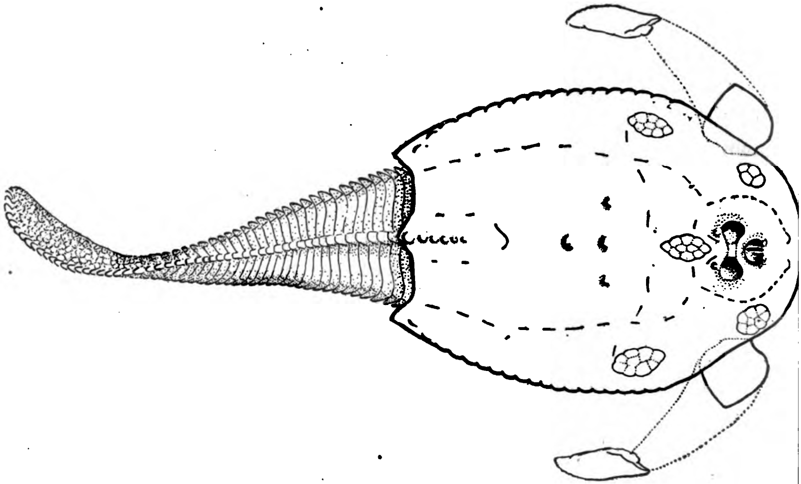


Fig. 369. Reconstruction of the head and trunk of *Trematas pis*, seen from above. Natural size. (After Patten.)

Fig. 370. *Palæospondylus gunni*, restored by Traquair; from the Old Red Sandstone, Caithness, Scotland. (After Dean.)

It had a slender column of vertebræ, modified at one end into a head and finned at the other for a tail, without ribs, paired fins, or any suggestion of limbs.

The *fishes* found in the supposed fresh-water deposits of the Devonian exceed in number and variety those found in contemporaneous marine formations. Perhaps the strangest of them were the *arthrodirans* (Fig. 371), probably related to the ancestors of lung-fishes (*Dipnoi*) which reached their climax at about this time. *Ganoids* were present, with many resemblances to amphibians, of

which they were, perhaps, the ancestors. Like lung-fishes, they appear to have been near their climax at this time, though they lived on till the Cretaceous. Sharks, now chiefly marine, seem to have lived in the open sea in the Devonian period, but their remains

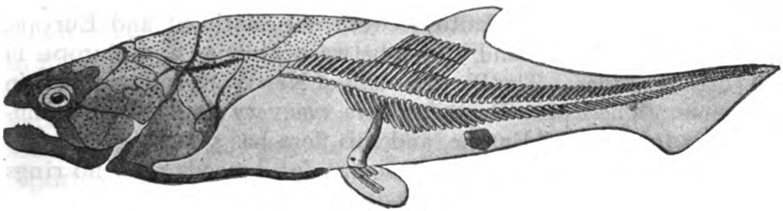


Fig. 371. A partial restoration of *Coccosteus decipiens;* from the Old Red Sandstone of Scotland. About ¼ natural size. (After Woodward.)

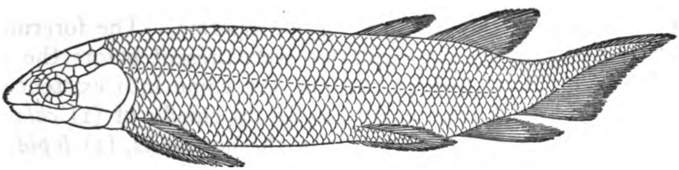


Fig. 372. *Dipterus valenciennesi*, restoration by Traquair; from the Old Red Sandstone, North Scotland; about 1/5 natural size.

are found also in the Old Red Sandstone and equivalent formations, so that they probably lived in fresh and brackish waters as well as in the ocean.

Shells, probably of fresh-water mollusks, and closely resembling living genera have been found in association with land plants and fishes.

### *Land Life*

Plants, snails, insects, myriapods, scorpions, and amphibians represent the known life of the land.

The Devonian period covers much of the early development, though probably not the actual beginning of terrestrial plant life. It saw the origin of ferns, scouring rushes, lycopods, the seed-bearing relatives of the conifers, and probably the "seed-bearing" ferns.[1] Devonian plants had, on the whole, little foliage, their leaves being spinoid and small. The presence of most of the fossil remains in fresh or brackish water or lowland deposits gives a suggestion of the habitats of the flora. It is inferred from the

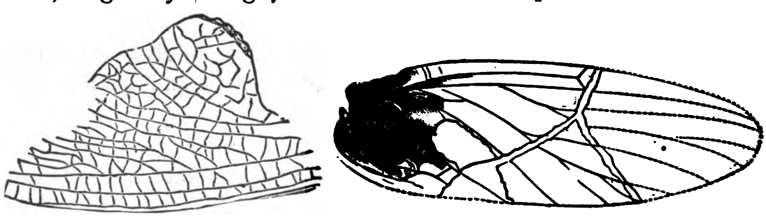
[1] David White, Jour. Geol., Vol. XVII, 1909. Many of the statements of the following paragraphs are from this article.

fossils that some of the plants were unable to stand alone, but sprawled about on the ground or clambered over other plants. Of the upland vegetation nothing is known.

The Middle Devonian flora of Maine is so like a flora of Scotland, Belgium, and the Rhine provinces, as to indicate the probability of the migration of land plants between our continent and Europe, perhaps by way of a land bridge between America and Europe in the high latitudes. The Portage flora of New York is found also in Bohemia. The Upper Devonian flora was very similar from Pennsylvania to southern Europe, and this flora has something in common with that of Australia. Devonian fossil woods show no rings indicative of seasons or long periods of drought.

The types of Devonian plants were similar to those of the next period. The dominant forms were fern-like plants, some of which were seed-bearing, and the lower gymnosperms. The forerunners of both lepidodendrons and sigillarias[1] were present before the close of the period. Angiosperms had not yet come into existence, so far as known. The forests were made up chiefly of (1) *calamites* (*Equisetales*) the gigantic ancestors of the horsetails, (2) *lepidodendrons*, gigantic ancestors of the clubmosses, and (3) *cordaites*, all of which were better developed later.

The record of the lower land plants is almost negative, except that, singularly enough, bacteria have been reported. The identification of such simple forms in fossilized woody tissue of so ancient a period is remarkable, though the presence of bacteria is altogether probable in itself, for the record of plant life should have been more perfect than it is, had decay not been promoted by bacteria.



A B

Fig. 373. A, *Platephemera antiqua*, Sc., St. Johns, N. B. (After Scudder.) B, *Xenoneura antiquorum*, Sc. From St. Johns, N. B. (After Scudder.)

The general aspect of the fern-like, seed-bearing plants was

[1] For classification, see p. 685.

very like that of existing ferns. The larger number were herbaceous, but there were tree-forms not unlike tree-ferns in general appearance. These plants were already far advanced in their evolution, though little is known of their antecedents. They are generally thought to have been the progenitors of cycads and of most or all other gymnosperms. In numbers, fern-like plants appear to have surpassed all others.

Numerous wings and other fragments of insects have been found, chiefly near St. Johns, New Brunswick. Myriapods (thousand legged worms), arachnoids (spiders), and scorpions have been reported, and also terrestrial mollusks.

# CHAPTER XIX

## THE MISSISSIPPIAN (EARLY CARBONIFEROUS) PERIOD

The time from the close of the Devonian period to the end of the Paleozoic era was formerly regarded as the *Carboniferous* period. But this interval is now divided into two or three divisions, each with the rank of a period. If three divisions are made (as here), the first is the *Mississippian* (*Subcarboniferous*, *Lower Carboniferous*) period. It represents a time of widespread submergence of the North American continent, and was brought to a close by widespread emergence. The second, the *Pennsylvanian* (*Carboniferous*, *Coal Measures*, *Upper Carboniferous*) period represents a time when the area between the Appalachian Mountains and the 100th meridian maintained a halting attitude, being now slightly above sea-level and now slightly below it. West of the Great Plains, submergence was rather general, as during the preceding period. The third division of the old Carboniferous period is the *Permian*, a time of notable crustal deformation, general aridity, and, during part of the period at least, low temperature.

### FORMATIONS AND PHYSICAL HISTORY

The following subdivisions of the Mississippian system are recognized in the regions indicated:

| *Mississippi River States* | *Pennsylvania* |
|---|---|
| 4. Chester (or Kaskaskia) series (including Cypress sandstone below, and Chester beds above). | 2. Mauch Chunk |
| 3. St. Louis series (including Salem limestone below and St. Louis and St. Genevieve limestones above). | |
| 2. Osage or Augusta (including the Burlington and Keokuk limestones, and Warsaw shale). | 1. Pocono |
| 1. Kinderhook (or Chouteau) | |

#### *East of the Great Plains*

In the early part of the Mississippian period, coarse sediments (sands and gravels, now a part of the *Pocono formation*) were gathering along the western border of Appalachia, while in the central part of the Mississippi basin the sediments of this stage (*Kinder-*

*hook*) were partly calcareous. At the same time, the area of Southern Michigan was a sort of bay or partly enclosed sea receiving sediment from surrounding lands. Most of these formations are marine, but the Pocono has yielded fossils of land life. The formations of this stage are less widespread than those of later stages.

In the second (*Osage* or *Augusta*) stage of the period, the sea of the interior was clearer, and the deposition of limestone was general. Submergence extended westward, probably to New Mexico on the one hand and to Montana on the other. The rich deposits of zinc ore (with some lead) in southwestern Missouri and eastern Kansas are chiefly in the Osage beds, though the metallic compounds were concentrated into ores at a later time.

East of the Cincinnati arch, which was probably an island at this time, the deposition of clastic sediments continued. Those of eastern Ohio constitute a part of the *Waverly* series. Farther east, the accumulation of sand and gravel continued, or had been succeeded by the deposition of the mud which constitutes the *Mauch Chunk* formation. The sediments of at least a part of this formation seem to have accumulated on land, rather than in the sea. In Maryland and elsewhere farther south, a formation of limestone (*Greenbrier*) lies between the Pocono and the Mauch Chunk.

*The St. Louis stage* marks the time of maximum Mississippian submergence, so far as the western interior is concerned (Fig. 374). Limestone deposition continued in the Mississippi basin. It was at this time that the Bedford limestone[1] of Indiana (*Salem* or *Spergen formation*), famous as a building stone, was deposited. Much of this limestone, long mistaken for oölite, is made up of the shells of foraminifera. Many of the great limestone caves in Kentucky and southern Indiana are in the limestone of this epoch. In Michigan, beds containing salt (brine) and gypsum were being laid down, as at certain earlier stages in the period.

In the northern part of the Appalachians, the Mauch Chunk shales were in process of deposition. Other names are applied to the contemporaneous deposits in the mountains farther south. Locally, deposits of this time contain both coal and iron ore.

The *Chester* stage of the period was marked by more restricted waters and more varied sedimentation. The deposits of this stage resemble in a general way those of the Kinderhook stage. Those

[1] This name as applied to this limestone, is a trade name. As a geological term, Bedford is applied to a member of the Waverly series farther east.

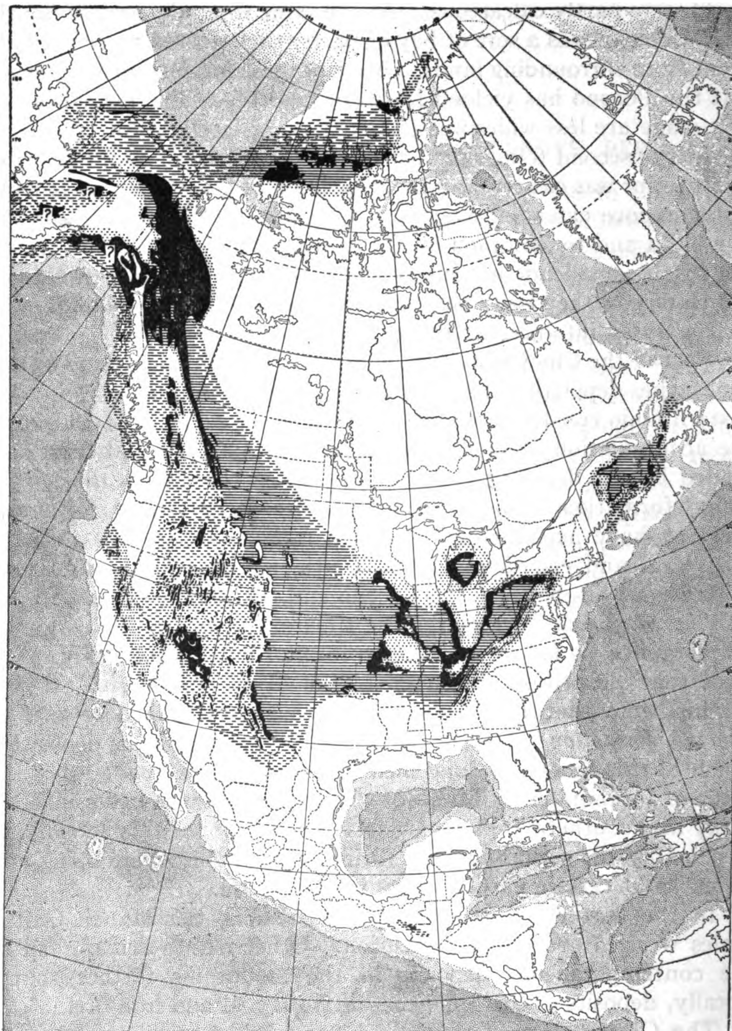


Fig. 374. Map showing the areas, in black, where the Mississippian system appears at surface. The map also shows where the Mississippian system is thought to exist, though buried (the lined areas), and the area from which it is thought to have been removed by erosion (the dotted areas). By inference, also, the map shows the relations of land and water during the Mississippian period.

were made while the sea was advancing on the land, these while it was retreating. Both are more restricted in their distribution than the beds of the intermediate epochs. In Illinois, the Chester sandstone bears oil locally.[1]

In summation it may be said that the Mississippian beds are largely clastic east of the Cincinnati arch, and largely calcareous west of it. It should be added also that the history of the Mississippi basin in this period is less simple than the preceding sketch might seem to imply, since there are several unconformities in the system, implying repeated emergencies of considerable areas. The extent of these unconformities has not been determined.

In Nova Scotia, the system rests, locally, on much older formations, and contains beds of red sandstone and gypsum.

*In the Great Plains and West of Them*

The Mississippian system is known in Oklahoma and South Dakota, where deformation and erosion have brought the strata to the surface (Fig. 374). Farther west the distribution of the system shows that the present mountain region, as far west as the 117th meridian, was mostly submerged, though there were perhaps numerous islands. North of the United States, also, marine conditions prevailed widely. Much of the system in the west is limestone, though clastic formations are not wanting. The system is exposed about many of the mountains, and over considerable areas in Arizona and perhaps in New Mexico. It rests on the Ordovician in many places, and locally overlaps all earlier Paleozoic systems, lying on the Proterozoic. In parts of Colorado (Leadville) the Mississippian limestone and dolomite constitute one of the richest ore horizons of the state. In many parts of the west the Mississippian system is unconformable beneath the Pennsylvanian.[2]

**Igneous activity.** According to present interpretations, there was great igneous activity in the west during this period. The area affected by vulcanism at this time, or soon after, extended from Alaska on the north to California on the south.[3] Dikes affect the system of Southern Illinois and adjacent parts of Kentucky, but the date of their intrusion is not known.

[1] Bain, Econ. Geol., Vol. III, and Bull. 2, Ill. Geol. Surv.

[2] The Mississippian is not differentiated from the Pennsylvanian on the maps of most of the western folios of the U. S. Geol. Surv., though the two are differentiated in the texts especially in the later folios.

[3] Dawson, Can. Geol. Surv., 1886, p. 85.

## *General Considerations*

**Thickness and outcrops.** In keeping with the variations in the sediments, the thickness of the Mississippian system varies greatly. In Pennsylvania, there is a thickness of 1,400 feet of sandstone (Pocono), with 3,000 feet of shale (Mauch Chunk) above it; but so rapidly do the formations thin westward, that in the western part of the same state the equivalent formations have a thickness of only 300 to 600 feet. In the region of the Mississippi it reaches a maximum thickness of about 1,500 feet. In Oklahoma, the thickness is about 1,800 feet, in the Black Hills 275 to 525 feet, in Colorado (Crested Butte region) 400–525 feet, and in northern Arizona (Grand Canyon of the Colorado), 1,800 feet.

**Close of the period.** At the close of the period, the eastern interior sea was contracted to narrow limits if not obliterated. Great changes took place in the western half of the continent too, for there is a widespread unconformity above the Mississippian system. In parts of the west, however, so far as now known, marine conditions prevailed uninterruptedly from the early Mississippian period to the later part of the Pennsylvanian.

This great unconformity, and the great changes in life which accompanied the emergence which it records, is the basis for regarding the Mississippian a distinct period.

## *Lower Carboniferous of Other Continents*[1]

In western Europe, two great series, or systems, are included under the Carboniferous, (1) the Lower Carboniferous, chiefly of marine origin, and (2) the Coal Measures or Carboniferous proper,

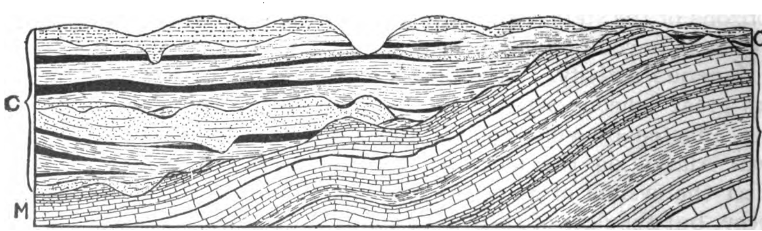



Fig. 375. Composite diagrammatic section, showing the unconformity between the Mississippian and Pennsylvanian systems in Iowa. (Keyes, Ia. Geol. Surv.)

[1] The term Lower Carboniferous is here used, instead of Mississippian, because it is the term in common use in Europe.

deposited partly in lagoons, marshes, and lakes, and partly in the sea. These systems correspond, in a general way, to the Mississippian and Pennsylvanian of North America. In the southern part of the continent the Lower and Upper Carboniferous formations are like the Mississippian and Pennsylvanian of western North America, in that both are chiefly marine. In eastern Europe the Lower Carboniferous is partly non-marine and coal-bearing, while the Upper Carboniferous is largely marine.

The Lower Carboniferous of western Europe is largely of limestone, which in Great Britain has received the name of "mountain

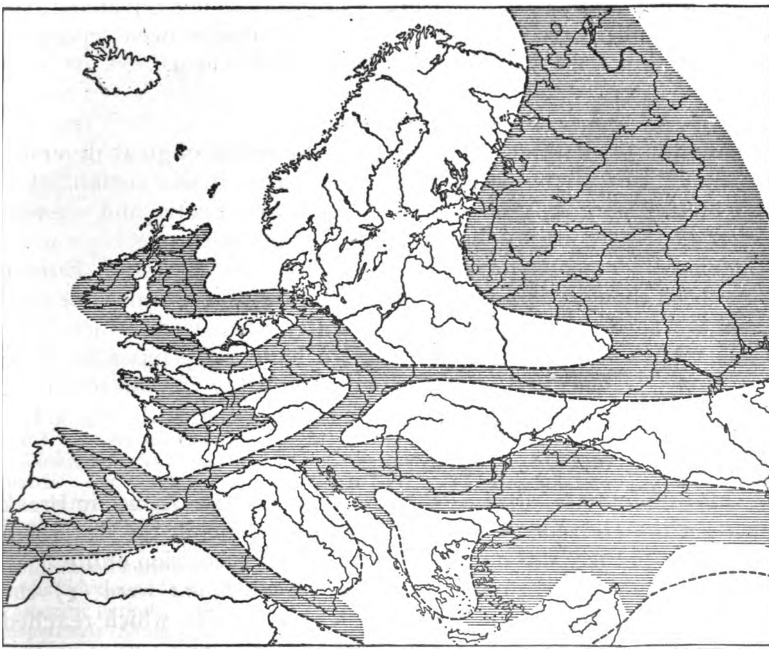


Fig. 376. Map showing the relations of land and water in Europe in the early Carboniferous period. The shaded parts represent areas of marine deposition. (After DeLapparent.)

limestone." East of the Rhine the Lower Carboniferous limestone is replaced by shale, sandstone, and even conglomerate, collectively known as the *Culm*. This phase of the system contains coal in some places.

The Lower Carboniferous of some parts of Great Britain and western Europe contains much volcanic rock. Some of the eruptions were probably submarine, and some subaërial.

The close of the early Carboniferous period was marked, in Europe, by widespread withdrawal of the sea from the area of the continent which it had covered. There were also some mountain-forming movements (folding), as in the Vosges Mountains, in eastern France, and elsewhere. The development of the Ural Mountains appears to have begun at about the same time. These changes shifted the areas of sedimentation notably.

In other continents, where geological work is less advanced, the Lower and Upper Carboniferous have not always been separated carefully, but the lower system exists in all of them.

### *Climate and Duration*

Most of the data at hand indicate the absence of great diversity of climate during the period, and suggest that it was genial. The salt and gypsum in Montana, Michigan, Nova Scotia, and western Australia, imply aridity, but it is not clear that aridity was general. Certain conglomerate formations (in the Culm) of western Europe have been thought to indicate glaciation, but the evidence does not seem to warrant this conclusion. Recently, phenomena which have been interpreted to imply floating ice have been reported from Oklahoma.[1] The duration of the period probably was not less than the average duration of the Paleozoic periods.

## LIFE

**Marine faunas.** Just as there was no great stratigraphic break between the Devonian and Mississippian systems in the American continent, so there was no radical break in the succession of life.

Conspicuous elements of the *Kinderhook fauna* were (1) the beginnings of the great deployment of the *crinoids*, which reached their climax later in the period; (2) *brachiopods*, which were transitional between Devonian and Later Mississippian types, the genus *Productus* being conspicuous (Fig. 377, *d. e.*); and (3) abundant *mollusks*, *pelecypods* (*i*, *j*, Fig. 377) being most numerous. *Trilobites* were few and small. Their high stage of ornamentation had passed, and the day of their disappearance was drawing near. Fishes, especially sharks, were abundant.

[1] Taff. Bull. Geol. Soc. Am. Vol. xx. p. 701.

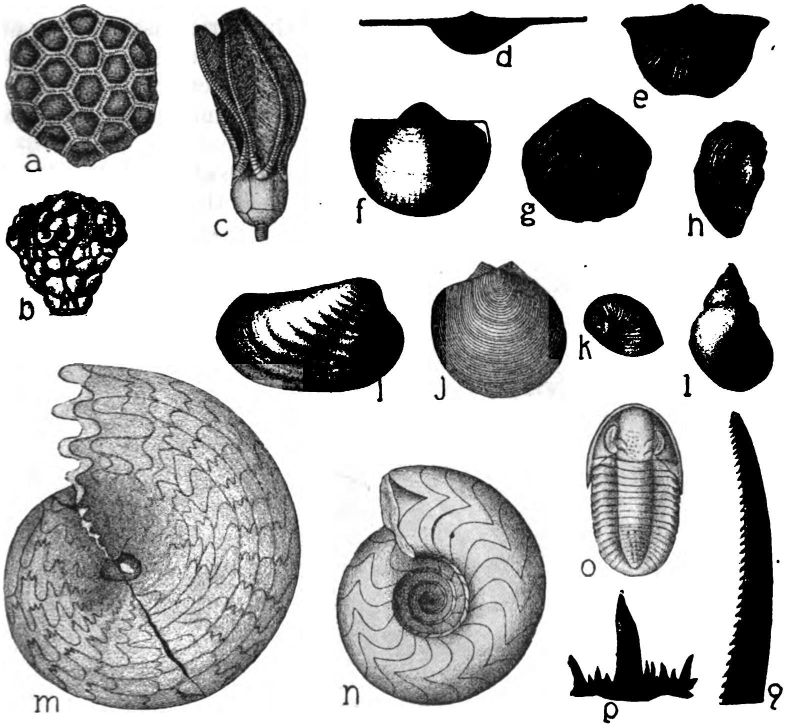



Fig. 377. Kinderhook Fossils: *a*, *Leptopora placenta* (White), a compound coral. *b*, *Actinocrinus senectus* M. and G., a distinctively Mississippian crinoid; *c*, *Dichocrinus inornatus* W. and Sp., one of the earliest crinoids with only two basal plates. *d-h*, brachiopods: *d*, *Spirifer biplicatus* Hall, a species retaining an elongate hinge line characteristic of the Devonian; *e*, *Spirifer marionensis* Shum.; *f*, *Productella pyxidata* Hall, a genus which had its greatest development in the late Devonian; *g*, *Paraphorynchus striatocostatus* (M. and W.), characteristic of Lower Kinderhook horizons of Iowa, Missouri, and Illinois; *h*, *Productus arcuatus* Hall, a genus developed from Productella, and characteristic of the Mississippian and later Paleozoic periods; *i*, *Grammysia hannibalensis* (Shum.), a pelecypod; *j*, *Pernopecten cooperensis* (Shum.), a pelecypod characteristic of certain of the higher Kinderhook horizons; *k*, *Platyostoma broadheadi* S. A. M., a capulid gastropod; *l*, *Macrocheilus blairi* (M. and G.); *m*, *Prodromites gorbyi* (S. A. M.), a widely distributed cephalopod and the earliest form showing secondary lobing of the sutures; *n*, *Muensteroceras oweni* (Hall), abundant in the famous Kinderhook goniatite bed at Rockford, Ind.; *o*, *Pröetus ellipticus* M. and W. Trilobites were few in the Kinderhook, and this one illustrates their characteristic lack of ornamentation; *p*, tooth of *Cladodus springeri* St. J. and W., a shark; *q*, a spine of *Acondylacanthus gracilis* St. J. and W.

The physical conditions of the Osage epoch furnish the key to the character of the *Osage fauna.* The extended shallow, clear sea

was a favorable field for the evolution of the varied assemblage of forms that had come together in preceding epochs under less favorable conditions. There is evidence also of rather free migratory communication with the Eurasian continent, since many species were common to America and Europe.

No single group so well characterizes the Osage fauna and expresses its dependence on physical conditions as the *crinoids*, whose abundance and diversity were climacteric (Fig. 378). Their rapid

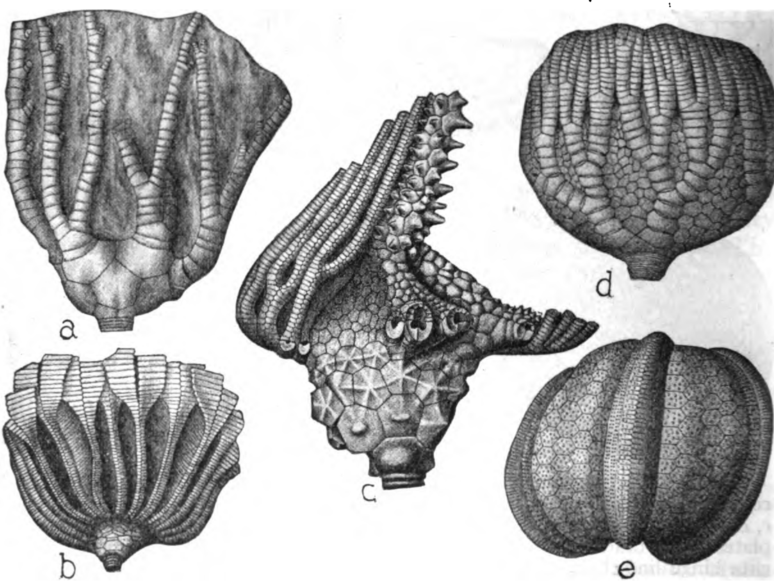



Fig. 378. OSAGE ECHINODERMS: *a-d*, crinoids; *a*, *Barycrinus hoveyi* Hall; *b*, *Eretmocrinus remibrachiatus* (Hall), having spatulate arms; *c*, *Actinocrinus lobatus* Hall, shows highly ornamented plates; *d*, *Forbesiocrinus wortheni* Hall, a flexible crinoid; *e*, a blastoid, *Oligoporus mutatus* Keyes.

decline after this epoch is one of the most remarkable incidents in the life history of the invertebrates. In the day of their glory, the crinoids were most prolific, as indicated by the fact that a single genus (*Batocrinus*), had more than a hundred species. Their ornamentation was notable, and as in the case of the trilobites, preceded their decline. The repetition of this phenomenon at different times and in different groups of organisms is worthy of notice, though its meaning is not altogether clear. Crinoids made large contributions

to the limestone of the period. Other echinoderms were not very abundant.

It is a matter of surprise that corals were so few, in view of the favorable physical conditions. Their paucity probably is to be explained by unfavorable organic conditions or relations, such as unrecorded enemies, or more successful rivals. *Brachiopods* (Fig. 379) were abundant, and some of their species ranged to the eastern

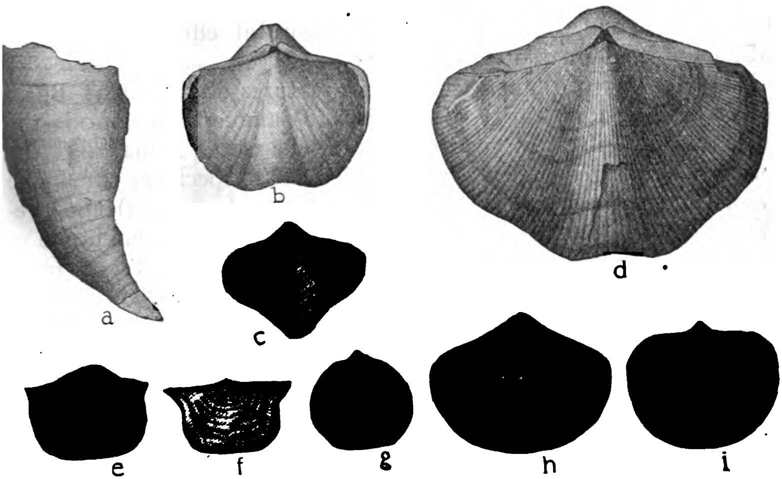



Fig. 379. OSAGE FOSSILS: *a, Zaphrentis centralis* E. and H., the most characteristic coral of the Osage. *b-i*, brachiopods: *b, Spirifer suborbicularis* Hall; a closely allied species occurs in Europe. *c, Athyris lamellosa* L'Eveille, a species common to America and Europe; *d, Spirifer logani* Hall, the American representative of *Spirifer striatus* of the European Mountain limestone; *e, Productus burlingtonensis* Hall, a species abundant in the Lower Osage; *f, Leptæna rhomboidalis* Wilck, a species which persisted from the Ordovician to the Osage; *g, Rhipidomella burlingtonensis* (Hall); *h, Reticularia pseudolineata* (Hall), a spire-bearing brachiopod closely allied to species in the European Mountain limestone; *i, Schizophoria swallovi* Hall, one of the last of the orthids.

continents. *Mollusks* were very subordinate. There were a few lingering *trilobites*, an abundance of *bryozoans*, some supposed *sponges*, and doubtless many forms not readily fossilized. Marine plants left but an obscure record.

*The Waverly fauna*, east of the Cincinnati axis, was more provincial than the Kinderhook and Osage faunas. It was the direct descendant of Devonian faunas that occupied the same ground, and had changed but slowly. It was modified by some immigration of

Kinderhook and Osage types, and took on slowly a Mississippian aspect, while retaining many Devonian characteristics. Its most prominent members were the *pelecypods*, as might have been anticipated from the silty conditions.

The *Great Basin fauna* of the first half of the period records a gradual evolution of the Devonian fauna of the same region, with perhaps the addition of a few immigrants from the west. After the Osage epoch, the Basin fauna united with the Osage fauna of the interior, and this union had an important effect on the later Mississippian faunas of the interior.

Previous to the union, the salient features of the Great Basin fauna were the (1) rarity of *crinoids*; (2) among brachiopods the absence of spirifers, so characteristic of the Osage fauna, and the presence of the genus *Productus*, closely allied to species of the Osage fauna and probably developed by parallel evolution; (3) the preponderance of pelecypods over brachiopods; (4) the abundance of gastropods, among which were air-breathers, the oldest aquatic pulmonates known; and (5) plentiful corals, the horn-shaped type predominating. Cephalopods and trilobites were few, and no fishes have been reported. Unless this is due to the imperfection of the record or of present investigation, it adds much to the evidence of the distinctness of the province, for fish abounded in the eastern sea.

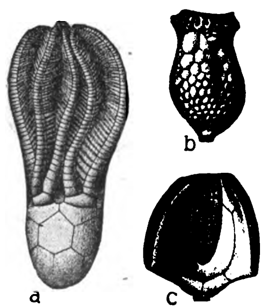



Fig. 380. Upper Mississippian Echinoderms: *a*, *Agassizocrinus dactyliformis* Shum., a crinoid which lost its stem and became a free swimming creature, at least in its adult condition; *b*, *Acrocrinus amphora* W. and Sp., a specialized camerate crinoid with a large number of supplementary plates introduced between the basal and radials; *c*, *Pentremites robustus* Lyon, a blastoid.

The barrier which separated the Great Basin and the Kinderhook-Osage seas appears to have been an elongated insular tract lying between the Rocky Mountains and the Great Basin. The yielding of this barrier about the close of the Osage epoch, by erosion or submergence, permitted the singular semi-Devonian, semi-Mississippian fauna of the west to invade the greater eastern sea. *The late Mississippian* (*St. Louis*) faunas of the interior include (1) the culmination of the cosmopolitan evolution of the marine life of the Mississippian period on the North American continent, and (2) the initiation of its

decline. The most distinctive feature was the commingling of the Great Basin and the Osage faunas. It introduced into the main Mississippian sea what seemed to be a retrograde change, for species of Devonian aspect that still lived in the isolated Great Basin province and elsewhere, migrated eastward, and their relics are found with species whose evolution had reached an advanced Mississippian phase.

*Crinoids* were less plentiful than in the Osage fauna, and notably changed (Fig. 380). Of one group which had upwards of 300 species in the Osage fauna, less than 25 species are known in the later faunas, and among the 25, no Osage species is found. Other groups of

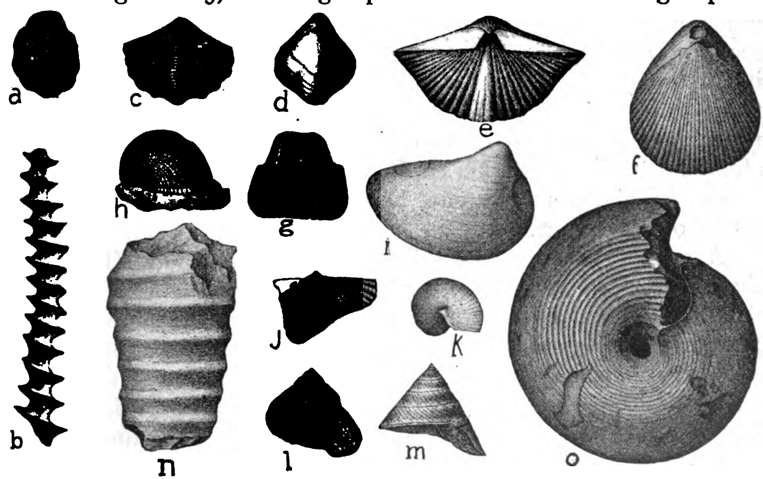



Fig. 381. Characteristic Upper Mississippian Fossils: *a*, *Endothyra baileyi* Hall, a small foraminifer, much enlarged, abundant in the Bedford limestone of Indiana, and often mistaken, in the past, for an oölitic concretion; *b*, *Archimedes swallovanus* (Hall), a bryozoan having a peculiar screw-like axis for the support of the colony. *c-h*, brachiopods: *c*, *Spiriferina spinosa* (N. and P.), a genus which developed from Spirifer, and has its greatest development in the late Mississippian and Pennsylvanian; *d*, *Seminula subquadrata* (Hall), a species closely related to Pennsylvanian types; *e*, *Spirifer increbescens* Hall, a species characteristic of the later Genevieve faunas; *f*, *Eumetria marcyi* (Shum.), a representative of a genus abundant in the Genevieve faunas. It was present in the Kinderhook, but has not been found between the Kinderhook and the closing stages of the Osage; *g*, *Productus fasciculatus* McCh.; *h*, *P. marginicinctus* Prout; *i* and *j*, pelecypods: *i*, *Schizodus chesterensis* M. and W.; *j*, *Conocardium prattenanum* Hall; *k-m*, gastropods: *k*, *Bellerophon sublævis* Hall; *l*, *Pleurotomaria nodulostriata* Hall; *m*, *Eotrocus concavus* Hall. *n* and *o*, cephalopods: *n*, *Orthoceras annulato-costatum* M. and W., one of the ancient type of straight cephalopods, occasional species of which persisted to the end of the Paleozoic; *o*, *Goniatites kentuckiensis* S. A. M.

crinoids, however, did not show so remarkable a decline, and new and curious forms appeared. *Blastoids* had their climax here so far as numbers of individuals are concerned, although there was greater diversity in the Osage fauna. A swift decline seems to have followed this climax, and the beautiful forms disappeared for reasons quite unknown.

*Polyps* seem to have profited by the decline of the crinoids, or for other reasons, for they were more numerous than in the Osage fauna. The simple horn-shaped forms were the most common. *Bryozoans* made a new departure in their mode of support. The delicate branches of their colonies could not extend themselves indefinitely without special means of support. As one mode of securing this support, the genus *Archimedes* (Fig. 381, *b*), which made its first appearance in the Osage, secreted an axis with a spiral flange upon which the colony spread itself, producing a unique form resembling slightly Archimedes' screw. Archimedes became so abundant in the Kaskaskia epoch that a part of the series is known as the Archimedes limestone, because of the great abundance of fossils of this genus.

A notable change took place in the brachiopods (Fig. 381), though *Productus* (*g* and *h*) continued to be abundant and characteristic. An odd feature was the small size of the brachiopods in the Bedford limestone of Indiana. The associated fossils of other kinds also were dwarfed, implying pauperizing conditions of some sort, for the species seem to be identical with those that grew larger elsewhere. It is not improbable that this limestone was deposited in a partially isolated body of water that was so highly charged with lime and other salts as to be somewhat unfavorable to life. A similar dwarfed fauna is recorded from Idaho.

Among *mollusks*, *pelecypods* (Fig. 381, *i*, *j*) were rather abundant, and some of them still had a Devonian aspect. Those in the Indiana foraminiferal limestone were small, like the brachiopods. *Gastropods* were more diversified than in the Osage fauna, and some Devonian genera which apparently had been absent from the Osage, reappeared. *Sharks* (Fig. 382) were important and other *fish* were present.

The most striking peculiarity of the fauna resulted from the invasion of the more conservative fauna of Devonian aspect from the sea of the Great Basin, and perhaps from a similar incursion of lingering forms from the Waverly gulf on the east. The remarkable

thing is that these should have succeeded, so far as they did, in impressing themselves on the composite result, and in giving tone to the whole. It is more natural to expect an antiquated fauna to be overwhelmed by a younger and more progressive one.

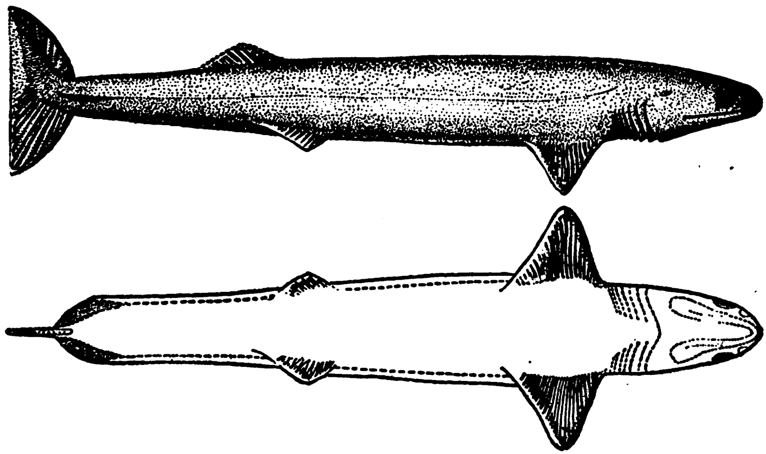


Fig. 382. *Cladoselache fyleri* Newb. Restoration by Dean. About 1/5 natural size. From Cleveland Shales, Ohio.

With the close of the Mississippian period, the chief center of life interest passes from the sea to the land, first to the vegetation of the Coal period, and then to land vertebrates. The history of the marine invertebrates will hereafter be followed with less fullness. With the introduction of fishes it had reached its great adjustments, and its further history bears a close likeness to the struggles and adaptations of the history already sketched.

**Evolution of fishes.** Many of the ancient invertebrates were fixed, and their migrations were confined to the early stages of their lives; but fishes were rovers. While restrained by conditions of food, temperature, etc., they were relatively independent of local conditions. They appear to have invaded effectually the open sea for the first time in the Devonian period, though at that time, marine fishes seem to have been fewer than those of inland waters. But by the middle of the Mississippian period, marine fishes were in unquestioned supremacy, while the fresh-water forms had declined notably, so far as the record shows. In the seas, the supremacy of the sharks was almost uncontested. They were more abundant,

apparently, than in any later period. Some 600 species are known, more than half of them from North America. The fossils are chiefly teeth, spines, and dermal ossicles. Three-fourths of the species had crushing or pavement teeth, adapted to breaking the shells of mollusks and crustaceans, and the trituration of seaweeds. The arthrodirans and lung fishes had declined, as compared with the Devonian period. Of fishes frequenting inland and coastal waters, probably the culminating type was of the order to which the modern garpike belongs. The curious tribe of ostracoderms (p. 686) had nearly or quite disappeared.

### *Land Life*

The record of land life is poor, but enough fossil plants have been found to show that the plant life of the early Mississippian land was little more than an expansion of that of the preceding period. There were, however, notable changes in detail. The geographic diversity of the Mississippian floras was somewhat greater than that of the Devonian. The mid-Mississippian flora is thought by White [1] to have had its origin on the islands of western Europe, and to have spread thence to Siberia and southward, even to South Africa and Australia; but by what route is not known. Seventy-five per cent of the species of a Mississippian flora of Argentina are identical with European species, a fact which suggests strongly a land bridge between South America and the continents just named.

The flora of the closing stages of the period indicates adverse conditions of life, and prepares the way for the great floral changes which followed. From this stage comes the earliest wood which shows rings.

The most interesting suggestion of advance in land life is found in the footprints of a supposed amphibian from the Mauch Chunk shale of Pennsylvania. They imply a stride of about thirteen inches, and a breadth between outer toes of eight inches. Nearly complete specimens of amphibia (*labyrinthodonts*) have been found in the Lower Carboniferous of Scotland.

Probably insects and their allies lived, but their fossils have not been found.

[1] Jour. of Geol., Vol. XVII, 1909.

# CHAPTER XX

## THE PENNSYLVANIAN (UPPER CARBONIFEROUS) PERIOD

### FORMATIONS AND PHYSICAL HISTORY

This system includes the Pottsville conglomerate (Millstone grit) below, and the Coal Measures above. Its most distinctive feature, so far as North America is concerned, is its coal.

### *The Pottsville Conglomerate (Millstone Grit)*

The lowest formation of the system in the Appalachian region is sandstone or conglomerate, having different names in different regions. From its conglomeratic phase in the east, it grades into sandstone in the interior. It has not been recognized in the western part of America. Over wide areas it is unconformable on the Mississippian system, as already noted. Locally as in parts of Illinois, the formation is oil-bearing. At various points in the east it contains thin beds of coal, and in the southern Appalachians, some thicker beds.

The formation varies in thickness from a maximum of some 1,500 feet in the Appalachians, to less than 100 feet in some parts of western Pennsylvania. It is so firmly indurated that the outcrops of its tilted beds have become ridges in many places.

### *The Coal Measures*

Above the Pottsville conglomerate and its equivalents in the central and eastern parts of the continent, lie the formations known as the Coal Measures. They consist of a succession of alternating beds of shale, sandstone, conglomerate, limestone, coal, and iron ore. The succession differs greatly in different regions, but shale perhaps recurs more frequently than other sorts of rock, and in thicker beds. Both the coal and some of the iron ore are in layers interstratified with the other members of the series, and are to be looked upon as strata of rock. Important as the coal and iron ore are from an economic point of view, they make up but a small part of the Coal Measures. There are many beds of coal in some regions, and some

Fig. 383. Map showing the areas where the Pennsylvanian system appears at the surface in North America. The map also shows, as in preceding similar cases, the areas where the Pennsylvanian system is thought to exist though buried (lined areas); the areas where it is thought once to have existed, but to have been removed by erosion (dotted); and by implication the relations of land and sea during the Pennsylvanian period.

of them have great thickness (40 to 50 feet); yet the proportion of coal in the Coal Measures is rarely so mueh as 1:40, and that of iron ore is much less. The classification of the Pennsylvanian system of the east now in common use is as follows:[1]

| | | |
|---|---|---|
| Pennsylvanian | 4. | Monongahela |
| | 3. | Conemaugh |
| | 2. | Allegheny |
| | 1. | Pottsville |

A twofold division is common farther west. Thus in Iowa the lower division is called the *Des Moines*, and the upper, the *Missourian.*

**Productive coal-fields.** The Pennsylvanian system does not contain coal in workable quantity everywhere, though coal is widely distributed as far west as the 96th or 97th meridian in Oklahoma, and nearly to the 100th meridian in Texas. The productive coal areas of the system in North America are six in number, as follows:[2]

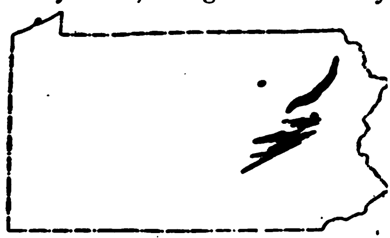


Fig. 384. Map showing the areas of anthracite coal in Pennsylvania.

(1) *The anthracite field*, of eastern Pennsylvania, with an area of 484 square miles. It includes several elongate, nearly parallel, synclinal basins (Figs. 384 and 385). From the associated anticlines, and from the neigh-

Fig. 385. Section across Panther Creek basin in the anthracite region of Pennsylvania, showing the structure and the coal beds (black). (Stoek, U. S. Geol. Surv.)

boring shallower synclines, the coal beds have been worn away. The strata of this field may once have been continuous with those of the next.

(2) *The Appalachian field*, which extends from Pennsylvania to Alabama (Fig. 386), has an area of about 70,000 square miles, of

[1] Prosser, Am. Jour. Sci., 4th series, Vol. XI, p. 191, 1901.

[2] 22d Ann. Rept., U. S. Geol. Surv., Pt. III, p. 15.

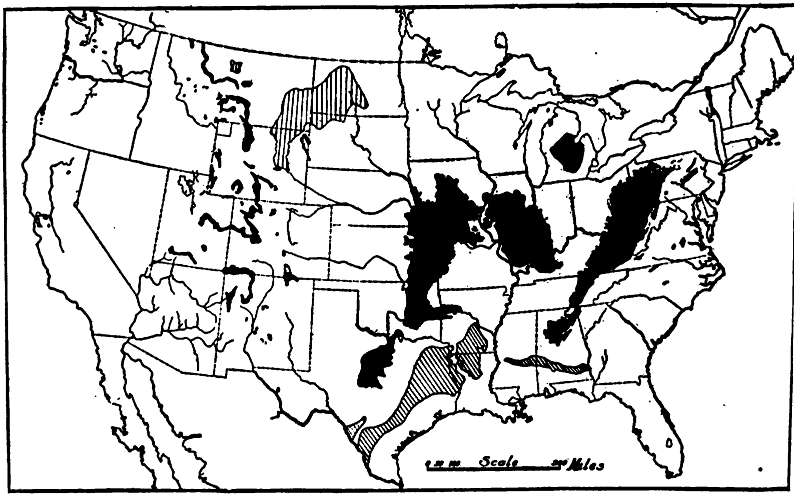



Fig. 386. Map showing the known distribution of coal in the United States. The black areas are the areas within which there is coal of the Pennsylvanian system (anthracite and bituminous). The areas marked by dots in Virginia and North Carolina represent Triassic (bituminous) coal. Those with vertical (lignite) and horizontal (anthracite, bituminous, and lignitic-bituminous) lines represent coal of the Cretaceous (Laramie) system, and those with diagonal (lignite) and crossed (bituminous and lignitic-bituminous) lines represent coal fields of Tertiary age. Some of the fields, as those of Washington and California, appear very small on this map. The Cretaceous and Tertiary areas include only those where there is known to be workable coal. (U. S. Geol. Surv.)

which about 75 per cent contains workable coal. The western edge of the sharply folded Appalachian belt is the eastern edge of the Appalachian coal-field. With few exceptions, the strata of this field are horizontal, or gently undulating.

(3) *The Northern Interior field*, confined to the southern peninsula of Michigan, covers an area of about 11,000 square miles. The strata of this field dip gently toward its center.

(4) *The Eastern Interior field*, centering in Illinois, covers an area of about 58,000 square miles (Fig. 386), and about 55 per cent of it is productive. This field is set off from the Appalachian field on the east, and from the Western Interior field on the west, by broad low anticlines from which the Coal Measures, if ever present, have been eroded.

(5) *The Western Interior and Southwestern fields* (Iowa to Texas) covers an area of about 94,000 square miles. On the west this field

is limited by the overlap of younger formations. Except in Arkansas and Oklahoma, where the strata are folded, the Coal Measures of this area are nearly horizontal.

(6) *The Nova Scotia-New Brunswick coal-field*, on either side of the Bay of Fundy, contains an area of about 18,000 square miles. The coal is bituminous, of good quality.

**Non-productive areas.** In the vicinity of Narragansett Bay, the Carboniferous system has great thickness, and locally rests on beds of Cambrian age. Coal occurs here, but it is too highly anthracitic (or graphitic) to burn readily. The beds are much deformed and are associated with igneous rocks. Carboniferous rocks occur at other points in New England, where they are partly igneous (Fig. 389) or meta-igneous, and partly meta-sedimentary.

**West of the Great Plains.** The system is widespread west of the Great Plains, and probably underlies the Plains themselves. With rare exceptions, the western beds are coal-less, the abundant coal of that region belonging to later systems. The coal-less phase of the system, the whole earth considered, is far more widespread than the coal-bearing.

In some parts of the west, the Carboniferous system includes formations which resemble the "Red Beds" of the next (Permian) system. This is the case in the southern part of the Rocky Mountain region, and in the plains adjacent, and here the separation of the Pennsylvanian system from the Permian is not very distinct, or has not been carefully worked out.

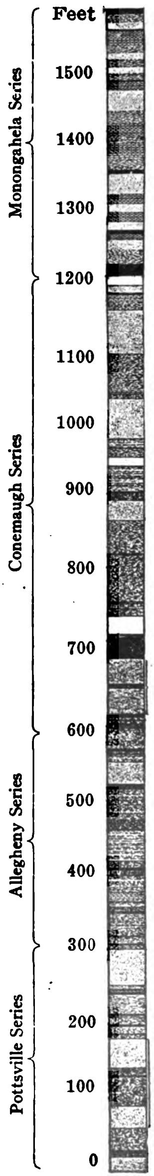



Fig. 387. Composite section of the Pennsylvanian system of Pa., compiled from various sources. The Pottsville portion of the section is from Mercer Co. (I. C. White); the Allegheny portion from Armstrong Co. (White [David] and Campbell); the Conemaugh portion from Fayette Co. (I. C. White); the Monongahela portion from Fayette Co. (Stevenson). The black bands represent coal, the checked pattern limestone, the dots sandstone, and the broken lines shale. (U. S. Geol. Surv.)

The Carboniferous system of the west includes all sorts of sedimentary rocks, among which are considerable thicknesses of limestone. They are exposed at many points (Fig. 383) and their existence over wide areas where they are now covered

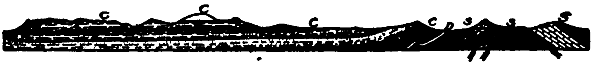


Fig. 388. Section showing the position and relations of the Carboniferous section near Estillville, Ky. *C*=Carboniferous (including Mississippian); *D*=Devonian; *S*=Silurian. Length of section about 16 miles. (Campbell, U. S. Geol. Surv.)

by later deposits is certain. The system is, however, not continuous. Numerous islands of older rock probably maintained themselves throughout the period, and a large area of land existed through-


Fig. 389. Section in northwestern Massachusetts, showing the position and relations of the Carboniferous system. *Cw*= igneous rock, Carboniferous; *Sc* (Conway schist) and *Sg* (Goshen schist) are Silurian formations; *Oh* (Hawley schist), *Os* (Savoy schist), and *Och* (Chester amphibolite) are probably Ordovician, though classed with the Silurian in the Hawley folio. (Emerson, U. S. Geol. Surv.)

out the Paleozoic era in western Nevada (west of long. 117°), and had an unknown extension north and south.

Figs. 390 to 392 show the positions and relations of the Mississippian and Pennsylvanian systems at various points in the west. The sections are from regions where the strata have been much disturbed by folding, faulting, and the intrusion of igneous rock.

North of the United States, Carboniferous strata (largely Mississippian) outcrop on the west side of the northward continuation of the Great Plains. These strata are probably continuous southward with the contemporaneous formations of the United States. Strata of the same age are found on both sides of the Gold Range of British

Fig. 390. Section showing position and relations of the Carboniferous system (as well as others) in the Yellowstone Park. *Æ*=Archean, *Є*=Cambrian, *S*=Ordovician and Silurian, *D*=Devonian, *C*=Carboniferous, *J*=Jurassic, *K*=Cretaceous. *N*=Neocene, and *anp*=igneous rock. Length of section about 17 miles. (Hague, Iddings, and Weed, U. S. Geol. Surv.)

Columbia. West of this range, the system includes much volcanic rock, the greater part of which was extruded before the close of the period. The system is continued northward into Alaska,[1] where it is less widespread than the Mississippian, so far

Fig. 391. Section showing the position and relations of the Carboniferous system at a point in Colorado. *Æ*=Archean; *€*=Cambrian; *O*=Ordovician; *M*=Mississippian; *Cw* and *Cm*=Carboniferous; *J*=Jurassic; *Kd*, *Kb*, *Kn*, and *Km*=Cretaceous. Length of section about 6 miles. (Eldridge, U. S. Geol. Surv.)

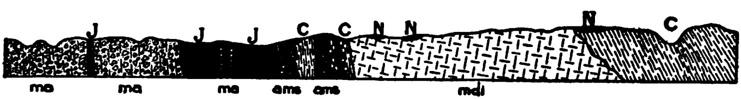


Fig. 392. Section showing the Carboniferous in the Sierras of central California. *C*=Carboniferous; *J* (Mariposa slates)=Jurassic; *mdi*=metadiorite; *ams*=Amphibolite schist; *N*=igneous rock of various sorts, of Neocene age. Length of section about 6½ miles. (Ransome, U. S. Geol. Surv.)

as present knowledge goes. In the Arctic lands of America, the Mississippian and Pennsylvanian are not differentiated. One or both are widespread.

**Thickness.** The thickness of the system has a wide range, but like all preceding systems of the Paleozoic, it is thick (4,000 to 5,000 feet) in the Appalachian Mountains. In the interior, it exceeds 1,000 feet in but few places; but in Arkansas, the Coal Measures have been assigned the remarkable thickness of more than 18,000 feet, from which it is inferred that there must have been land close at hand capable of supplying sediments in great quantity. This was probably the axis of the Ouachita uplift. In Texas, the thickness of the system ranges up to 5,000 feet, and in the west it is even thicker.

## *Coal*

The general conditions under which sandstone, shale, and limestone originate have been outlined, but there has been no occasion heretofore to consider the formation of coal. From its economic importance, coal has been studied with more care than most sorts

[1] Brooks, Professional Paper 45.

of rock, and geologists are agreed, in a general way at least, as to its mode of origin.

**Origin.** There is no doubt that coal is of vegetable origin. Except by the accumulation of vegetable matter, no way is known by which such beds of carbon could be brought into existence. Furthermore, the coal and its associated shales contain abundant remains of plants, in places even recognizable tree-trunks in the form of coal, and microscopic study has revealed the fact that much coal is but a mass of altered, though still recognizable vegetable tissues. Concerning the exact manner in which the beds of vegetable matter accumulated, and the conditions under which it was converted into coal, there is some difference of opinion.

Much coal is essentially pure, containing little matter of any sort which was not in the plants which gave origin to it. Purity does not mean freedom from ash, since mineral matter, which on combustion becomes ash, is present in all plants. Along with the large amount of coal which is nearly pure, there is much which contains some earthy matter. Where the admixture of earthy matter is small, the coal is still usable; but from poor coal of this sort, there are all gradations into carbonaceous shale.

The purity of some coal-beds over great areas warrants the conclusion that they were made of vegetation which grew where the coal is. The character of the vegetation shows that it grew on land or in swamps. Had it been washed down from its place of growth to the situations where the coal is, it should have been mixed with earthy sediment, and the product, after the necessary changes in the vegetable matter, would have been very unlike the purer coal-beds. Furthermore, the nearly uniform thickness of many of the coal-beds over great areas, some of them many thousand square miles, is a strong objection to the hypothesis that its substance was drifted together by any process whatsoever.

Some other facts which support the theory that the vegetation grew where the coal-beds are, may be noted. (1) Beneath many coal-beds there is a layer of clay with roots (or root marks) in the position of growth. The clay seems to have been the soil in which the coal vegetation was rooted. (2) In association with the coal-beds, stumps of trees are found still standing as they grew (Fig. 393). (3) In coal-beds, or in the associated layers of shale, imprints of the fronds of ferns or fern-like plants are found. They are in places so numerous and so perfect as to indicate that they were

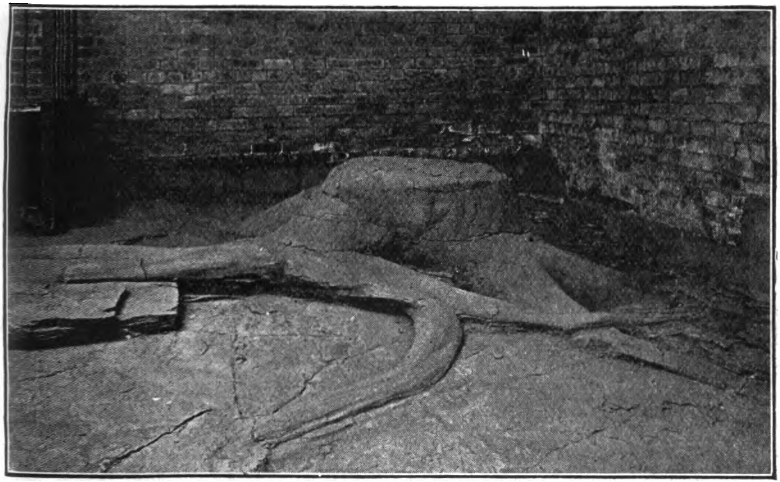


Fig. 393. Showing a stump standing as it grew in Coal Measures, near Glasgow, Scotland.

buried where they fell, without being drifted by moving waters from one place to another. (4) In many cases, the layer of rock next overlying a coal-bed contains abundant remains of vegetation, especially in its lower part, as if the conditions which brought about its deposition resulted in the destruction of the forest growth which had preceded. In such situations, trunks of trees 50 and 60 feet long, and 2 or 3 feet in diameter, have been found.

While it is confidently believed that most of the workable coal represents the growth of vegetation *in situ*, it is not to be understood that coal was never formed from vegetation which drifted together.

In the formation of a coal-bed, three things are to be accounted for: (1) The conditions under which the necessary quantities of vegetable matter accumulated; (2) how it was kept from decay; and (3) how changed into coal.

**Accumulation of organic matter.** Large marshes, or marshes in low surroundings, are the only places where vegetable matter is now accumulating in quantity, with little admixture of sediment. Thus in the marshes along some parts of the Atlantic coast (Fig. 394), there are quantities of organic matter which, locally, is mixed with little sediment. In Dismal Swamp, the stems, branches, leaves, and fruits of the trees, shrubs, and herbs which grow there,

have been long accumulating, and little sediment is mixed with them. In cypress and mangrove swamps, too, there are considerable thicknesses of vegetable matter nearly free from mud, etc. The multitude of marshes and peat-bogs in the United States and Canada are further illustrations of the accumulation of vegetable matter, in some cases mixed with abundant sediment and in some nearly free from it.

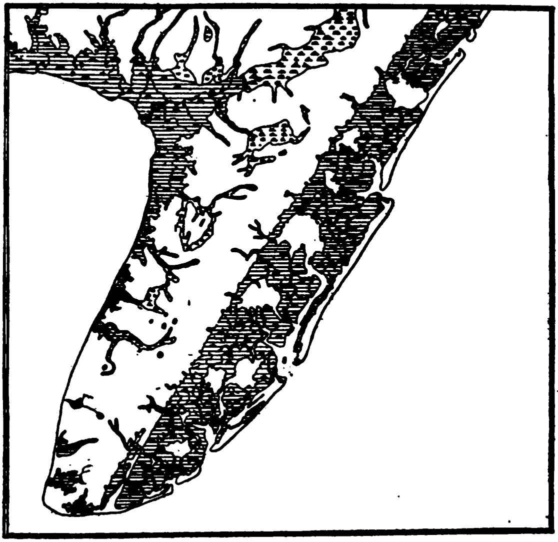


Fig. 394. Map of the Cape May peninsula, showing coastal marshes. The unshaded areas inside the coast line are dry land.

The vegetation in swamps need not be more luxuriant than that on moist lands which are not swampy. On fertile prairies and in some forests the annual growth of vegetation is great; but since the leaves, fruits, twigs, and trunks decay as they fall, the larger part of their substance is returned to the atmosphere. In a moist region there is more growth (and therefore more death) of vegetation than in a dry one, and a better chance that decay will not keep pace with death.

**Preservation of vegetable matter.** Where vegetation falls into water, as in marshes, it undergoes slow change different from the decay suffered by vegetation on dry land. It is the partial preservation of organic matter in the water of marshes and ponds which converts them into peat-bogs, for peat is nothing more than accumulated vegetable matter undergoing those changes to which vegetable matter in water is subject. Under favorable conditions, the peat of a bog may become very deep, as in the Dismal Swamp. In and about marshes and swamps, therefore, we find the conditions

for the accumulation of considerable thicknesses of vegetable matter, some of it nearly free from sediment, and at the same time the conditions which keep it from complete decay.

**Conversion into coal.** While the vegetable matter is not destroyed, it is not preserved intact. The approximate composition of wood and peat are shown by the following analyses (ash omitted).

| | *Carbon* | *Hydrogen* | *Oxygen* | *Nitrogen* |
|---|---|---|---|---|
| Wood | 49.66 | 6.21 | 43.03 | 1.10 |
| Peat | 59.50 | 5.50 | 33.00 | 2.00 |

The relative atomic proportions of carbon, hydrogen, and oxygen in cellulose are expressed by the formula $(C_6H_{10}O_5)_x$. In the air, the carbon and the hydrogen of the wood unite with oxygen of the air or of the wood itself, forming carbon dioxide and water, the principal products of the decay of vegetation. But under water the atmospheric oxygen is largely excluded, and the elements of the wood are thought to unite with one another to a larger extent, while the oxygen of the air plays but a subordinate part. One of the common products of decay under such circumstances is $CH_4$ (marsh-gas), which escapes into the air. The formation of this gas exhausts the hydrogen of the organic matter four times as rapidly as the carbon. If the carbon and oxygen of the wood are given off combined as $CO_2$, the oxygen is consumed twice as fast as the carbon. If the hydrogen and oxygen of the wood are liberated as water, the result is to increase the proportion of carbon remaining.

While the exact quantitative relations of the reactions which take place are not known, and are probably not constant, the following table[1] suggests certain changes which might take place, and the products which would remain at certain stages:

$$12\ C_6H_{10}O_5 \text{ (cellulose)} - \left\{\begin{matrix} 20\ H_2O \\ 8\ CO_2 \\ 2\ CH_4 \end{matrix}\right\} = C_{62}H_{72}O_{24} \text{ (peat).}$$

$$C_{62}H_{72}O_{24} \text{ (peat)} - \left\{\begin{matrix} 6\ H_2O \\ 4\ CO_2 \\ CH_4 \end{matrix}\right\} = C_{57}H_{56}O_{10} \text{ (brown coal).}$$

$$C_{57}H_{56}O_{10} \text{ (brown coal)} - \left\{\begin{matrix} 3\ H_2O \\ CO_2 \\ 2\ CH_4 \end{matrix}\right\} = C_{54}H_{42}O_5 \text{ (bituminous coal).}$$

$$C_{54}H_{42}O_5 \text{ (bituminous coal)} - \left\{\begin{matrix} 2\ H_2O \\ CO_2 \\ 5\ CH_4 \end{matrix}\right\} = C_{48}H_{18}O \text{ (anthracite coal).}$$

[1] Prepared by Rollin T. Chamberlin.

From this table it will be seen that the process which converts vegetable matter into coal is characterized by progressive changes in the nature of the chemical decomposition. The elimination of hydrogen and oxygen ($H_2O$) probably is the dominant change in the production of peat from cellulose. Second in importance at this stage is the removal of oxygen in the form of $CO_2$, while the liberation of methane ($CH_4$) is of still less importance. As the alteration of the peaty material progresses through successive stages to coal, less and less water and carbon dioxide are given off, and there is an increase in the proportion of $CH_4$ set free. Laboratory investigations have shown that while $CO_2$ may constitute an important part of the free gas held in the pores of some of the Cretaceous coals, the gas which escapes from the more advanced stages of Pennsylvanian anthracite coal is largely $CH_4$. The burial of the peat compresses it, and the physical change resulting is a part of the process of coal-making.

If coal-beds represent former swamps, as they are believed to, we have still to inquire into the conditions under which such extensive swamps existed, and to seek the explanation of their recurrence (one for each coal-bed) in many regions.

The first condition for a swamp is lack of drainage, and the second a sufficient, but not an excessive amount of water. Enough to stop the growth of vegetation would be excessive, and too little to preserve it after its growth and death, would be insufficient.

During the widespread movements which affected the eastern interior at the close of the Mississippian period, great areas appear to have emerged from the sea. Early in the Pennsylvanian period, considerable tracts which were not submerged stood so low as to be ill-drained, or undrained, and constituted marshes. Climatic conditions were such as to permit the growth of abundant vegetation in the marshes, where, after death, the vegetable matter underwent changes of the nature suggested above. The marshes were thus converted into peat bogs. Some of the great coal-swamps probably came into existence along shores, and some in shallow inland basins or undrained areas.

Each coal-bed represents the accumulated vegetable growth of a long period. It would appear that the growth and accumulation of vegetation was repeatedly brought to an end by subsidence which let the water (sea, lake, or aggrading stream) in over the marshes, drowning the plants, and burying the organic matter which

had already accumulated under sediment which the submergence brought in its train. A second coal-bed in the same region points to the recurrence of swamp conditions, and means either (*a*) that after submergence and burial of the organic matter, slight emergence reproduced the conditions for bogs; or (*b*) that by sedimentation the sea or lake bottom where the first bog had been was built up to water-level, restoring swamp conditions.

The number of coal-beds is, in many places, great. In some parts of Pennsylvania it exceeds 20; in Alabama, 35 (not all workable); in Nova Scotia (including some dirt-beds) about 80; but in the Mississippi basin west of the Appalachians, the number is in most places less than a dozen. In Illinois the workable beds are nine.

**Extent and relations of coal-beds.** The widespread distribution of coal does not mean that any one marsh necessarily covered the whole of any one great coal-field. Some coal-beds, however, are of great extent. Thus the Pittsburgh bed is worked over an area of some 6,000 square miles [1] in western Pennsylvania, Ohio, and West Virginia, and has at least an equal extent where too poor to be generally productive. Many coal-beds, on the other hand, are not extensive. From their thicker portions they thin out in all directions, grading into black shale in many places. Many facts suggest that within the general area of a coal-swamp there may have been elevations (islands), interrupting the continuity of the swamps, and therefore of the coal-beds.

**Varieties of coal.** The ways in which the different varieties of coal arose have never been determined precisely. In general, anthracite coal occurs in mountainous regions, where the coal and other layers of rock with which it is associated have been subject to much dynamic action. Thus, in the mountains of eastern Pennsylvania (Fig. 384) the coal is mainly anthracite, while in other coal-fields of the same age, where the strata are deformed much less, the coal is bituminous. In Arkansas, where the strata have been subject to some, but not to extreme dynamic action, the coal is semi-anthracitic.[2] Where the dynamic metamorphism of the associated rock has been great, as in Rhode Island, the coal has gone beyond the anthracitic stage. Anthracite coal is found also in some places (not in the Coal Measures of the United States) in contact with

[1] White, West Virginia Geol. Surv., Vol. II, p. 166.
[2] Ann. Rept. Ark. Geol. Surv., 1888, Vol. III.

intrusions of igneous rock. Other sorts of sedimentary rock are metamorphosed in similar situations.

These phenomena suggest that anthracite is metamorphic coal, produced from bituminous coal by processes similar to some of those which metamorphose other sorts of rock. The fact that most metamorphic coal is found in regions where erosion has exposed its beds (Fig. 385) led to the conjecture that exposure of the coal might be a factor in the problem, the exposure favoring the escape of the volatile constituents, and so aiding in the transformation of soft coal into hard. Some beds of bituminous coal are, however, exposed freely. Both dynamic action, involving pressure and heat, and exposure would seem to be conditions favoring the development of anthracite, but it does not follow that these are the only factors in the problem, or that anthracite coal has never been produced in other ways. White has advanced the idea that deep-seated, horizontal thrust movements are the essential cause of devolatilization[1].

There are several varieties of bituminous (soft) coal, some of which appear to depend on the nature and extent of the decay of the vegetable matter before its burial, and some on the degree to which the devolatilizing processes have been carried since burial. Recent studies seem to indicate that the kind of vegetation entering into the coal may have an important effect on the product. Some coal seems to be made up largely of algæ, or of the spore-cases of certain plants, and such coal has rather distinctive qualities, if recent interpretations are correct.

### *Other Products of Economic Value*

The *iron ore* of the Coal Measures occurs in layers, or in the form of nodules concentrated at a given horizon, forming a nearly continuous layer. The iron of the Coal Measures seems to have been deposited largely as a precipitate from the waters of inland and local basins while the other members of the system were being laid down. Dissolved by the land waters from the soil and rocks, it was brought to the marshes in some soluble form. In the marshes, it was precipitated in the form of iron carbonate or iron oxide. Subsequent oxidation has changed some of the original carbonate into the oxide. The principal iron ores of the system occur in Pennsylvania and eastern Ohio. The system yields *oil and gas* in some places, as in Oklahoma, Kansas, and Illinois.

[1] David White. *Economic Geology*, Vol. III.

## *General Considerations*

**Geographic conditions in the eastern interior.** Returning to the system of which the coal-beds form a small part, it is to be recalled that the formations represent an alternation of marine, lacustrine, and marsh conditions. The cause of the alternation was probably geographic, but it is not to be inferred that geographic changes were more frequent at this time than during other periods. Their record is conspicuous because the land was near sea-level, so that extensive submergence and emergence resulted from slight changes of relative level of land and sea. Equally frequent and equally extensive movements would leave no such record of themselves, if the surfaces concerned were far above or far below sea-level. It was oscillation just above and just below water-level (or base-level) which allowed the record to be so clearly preserved. How far the oscillations were due to warpings of the land, and how far to changes in the level of the sea, cannot be determined; but when we recall that the ocean-level must respond to every deformation which affects its bottom, and to every stage of filling, it is strange that its level is in a nearly perpetual state of change.

In general, it may be said that the movements of the crust which have been of most importance, from the point of view of continental or biological evolution, are not those which have affected high land or deep sea bottom, but those which have converted sea bottom into land, or land into sea bottom. Such changes are most likely to have taken place where land was low, or water shallow. From the point of view of geology, therefore, the *critical level* of crustal oscillation is the level of the sea.

**Duration of the period.** So uncertain is our knowledge of the duration of geological time that all sorts of data which can be made to throw light on the subject are of interest, even though they do not lead to trustworthy numerical conclusions. Under favorable conditions, a foot of peat may accumulate in ten years or even less; but the common rate is probably much slower. A vigorous growth of vegetation has been estimated to yield annually about one ton of dried vegetable matter per acre, or 640 tons per square mile. If this annual growth of vegetable matter were all preserved for 1,000 years, and compressed until its specific gravity was 1.4 (about the average for coal) it would form a layer about seven inches thick. But it has been estimated that four-fifths of the vegetable matter in

peat bogs escapes as gas ($CO_2$, $CH_4$, etc.), while the peat is being changed to coal. If this is true, the seven-inch layer would be reduced to less than one and one-half inches, and a layer one foot in thickness would require between 8,000 and 9,000 years. The aggregate thickness of coal is as much as 100 feet in many places, and as much as 250 feet in some. At the above rate of accumulation, periods ranging from nearly 1,000,000 to nearly 2,500,000 years would be needed for such thicknesses. It should be borne in mind, however, that much depends on the rate of growth of Carboniferous vegetation, which is not known.

On the other hand, these figures refer to the coal only, not to the Coal Measures. The greater part of the Coal Measures is shale and sandstone, and of these formations there are thousands of feet, even where the sediments were fine and their accumulation probably slow. It would hardly seem unreasonable to conjecture that their deposition may have consumed as much time as that of the coal. Doubling the above figures, we get 2,000,000 and 5,000,000 years respectively, figures which must be taken to mean nothing more than that the best data now at hand indicate that the Pennsylvanian period was very long.

**Close of the period.** After the long period of oscillation above and below the critical level recorded by the Coal Measures, the interior east of the Mississippi was brought above the level of the sea, not to sink beneath it again during the Paleozoic era, and some of it at no later time. This emergence marks the close of the Carboniferous, and the inauguration of the Permian period. It is also probable that the deformative movements which were to develop the Appalachian Mountains began at this time. There were notable changes also in the western half of the continent, for the Permian system is much less widespread than the Pennsylvanian. Where the Permian occurs, its constitution and fossils indicate not only different relations of land and water, but different conditions of erosion.

## *Foreign Countries*

**Europe.** As in America, the oldest formation of the Upper Carboniferous in Europe is in many places a conglomerate and sandstone formation, called the *Millstone grit*, in England. The Coal Measures consist principally of shales, with sandstone and limestone. Associated with these commoner sorts of rock, there are beds of coal

and clay-iron-stone, both of which occupy positions corresponding, in essential respects, with those of similar formations in eastern North America. There is workable coal in Great Britain, Ireland, Belgium, France, Spain, Germany, Austria, and Russia, but the total area of productive coal in Europe is much less than in America.

In Russia, as already noted, the Lower Carboniferous (Mississippian) contains much coal, while the Upper is chiefly of limestone; but in southern Russia (Donetz coal-field) there is coal in the Upper (Pennsylvanian) division. The Upper Carboniferous limestone of Russia (*Fusulina limestone*) is similar to that of southern Europe. The faunas of the marine part of the system in Europe have much likeness to those of western North America, suggesting that marine life was able to pass between these continents, via northern Asia.

Igneous rocks are associated with the Upper Carboniferous formations of sedimentary origin in western Europe. Their extrusion seems to have been an accompaniment of the crustal disturbances which affected western Europe in the course of this period. These movements appear to have been greatest during the Upper Carboniferous period (after the Westphalian epoch).

**Other continents.** The Upper Carboniferous of *Asia* is represented by both marine and non-marine formations. The non-marine phase, with numerous beds of coal, is found in Asia Minor, on the east side of the Middle Urals, and in northern and eastern China, reaching to northern Tibet on the one side, and to Mongolia on the other. The Carboniferous of some parts of China contains coal-beds of great thickness. The system is also present in India.

The Carboniferous formations of northern Africa are similar to those of southern Europe, but in southeastern Africa, a coal basin has been reported in Zambesi.[1]

The Carboniferous system is well developed in *Australia* where it is not in all places clearly separated from the Permian. Both the Carboniferous and the Permo-Carboniferous systems contain coal.

In *South America*, rocks of Late Carboniferous age are somewhat widely distributed. In southern Brazil they contain much coal.[2] The system is widespread in the lower part of the basin of the Amazon, where it rests on older formations unconformably, and is not generally coal-bearing.

[1] Kayser, Geologische Formationskunde, p. 207.

[2] White, I. C. *Commissão de Estudos das Minas de Carvão de Pedra do Brazil*, 1908.

## LIFE

With this period the chief biological interest shifts from sea to land, and centers in the vegetation and the amphibians.

### *Plants*

Plant life was very abundant in this period, and its record is unusually full and perfect. Its completeness has doubtless given this flora an undue prominence over those which preceded and succeeded it; yet it was really a great period in the history of plant life. Angiosperms (flowering plants, p. 685), the dominant plants to-day, had not yet appeared, but gymnosperms (the group to which pines belong) were abundant, and *pteridophytes* (ferns and related plants) probably made their greatest display at this time. All the great divisions of this group (p. 685) were present, and all of them were nearly or quite at their climax. Of lower plants, little is known. The most rapid evolution of floras was perhaps in the Pottsville epoch. Half the genera of that epoch scarcely survived it, and few of them lived after the Allegheny epoch.

The early floras were widely distributed. Thus three floras in Asia Minor may be correlated severally with three floras of the Pottsville series. The place of origin of these early floras is not known with certainty, but present evidence points to western Europe and eastern North America, with an Arctic land connection. The late Pennsylvania floras are less sharply separated from the early ones in North America than in Europe. The later floras indicate greater diversity of climate than the earlier.

The dominant plants of the period belonged to five groups: (1) the horse-tail family (*Equisetæ*), (2) *sphenophylls*, now extinct, (3) *lycopods*, or club mosses, (4) *fern-like plants* (*pteridosperms*), and (5) *Cordaites*, a group of gymnosperms. To this list *ferns* should perhaps be added.

*Ferns* were a minor element of the Pennsylvanian flora, though fern-like leaves are the most abundant of the plant fossils. It is now known that most of them belonged to seed-bearing plants and not to ferns. Nevertheless, true ferns were present. Species still live which, so far as outward form is concerned, might be referred to Carboniferous genera.

The *horse-tail group* (*Equisetales*) was represented by calamites (tree horse-tails), a conspicuous element in the Pennsylvanian flora. They must have been graceful trees, of the same general habit as

modern horse-tails, except for their large size. The largest modern tropical representatives of the group have slender stems 30 or 40 feet high, whereas the Pennsylvanian calamites reached a foot or two in diameter and probably 60 to 90 feet in height. They had hollow stems, or a core of pith, and casts of the interior are common. Branches from the trunk were comparatively few, and in whorls.

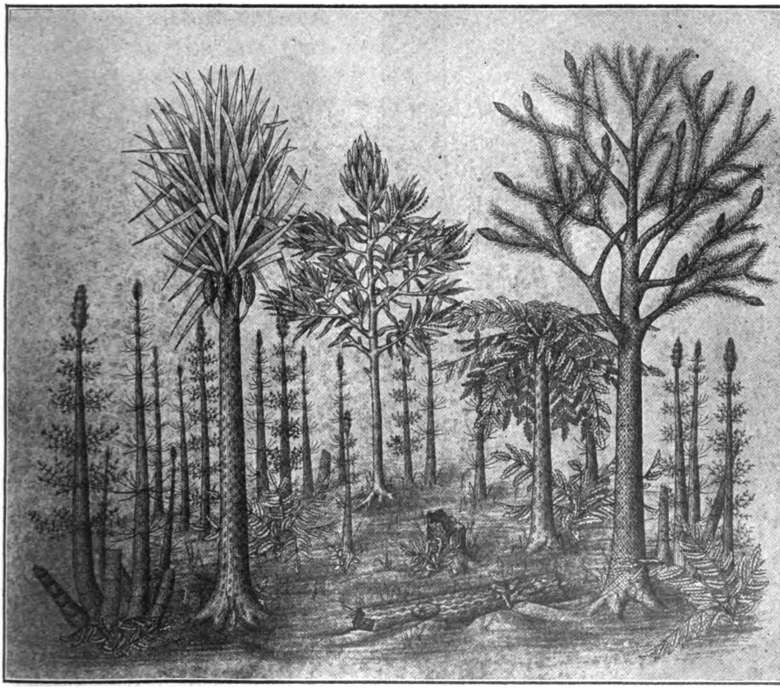


Fig. 395. A composite group of leading CARBONIFEROUS PLANTS, adapted from restorations by various paleobotanists, by Mildred Marvin. In the foreground at the right, *Lepidodendron;* at the left *Sigillaria;* in the right center rear, a tree fern; in the left center rear, *Cordaites;* at the extreme right and left, *Calamites.*

The leaves also were in whorls (Fig. 395) and dwarfed, though larger than in the modern type. Their roots were of the type commonly found under water or in wet places, and the calamites probably frequented swamps and lowlands. Roots are known to have been sent out as much as nine feet above the base of the stem.

They were probably associated in thickets and jungles, like canebrakes and bamboos. Their history may run far back, as they were well differentiated in the Devonian; but their ancestry is uncertain. The stems of adult calamites are so unlike those of modern horsetails that their kinship was long unrecognized, and calamites were thought to be gymnosperms; but it is now known that the stems of

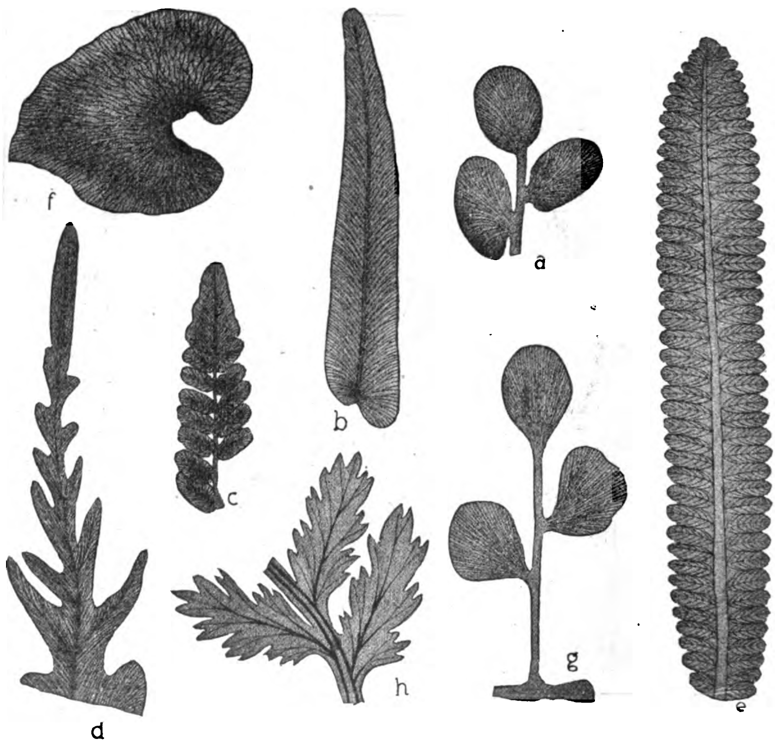



Fig. 396. GROUP OF FERN FRONDS: *a*, *Neuropteris auriculata*, Brgt.; *b*, *N. angustifolia*, Brgt.; *c*, *N. vermicularis*, Lx.; *d*, *Odontopteris cornuta*, Lx.; *e*, *Pecopteris unita*, Brgt.; *f*, *Dictyopteris rubelia*, Lx.; *g*, *Archæopteris bochsiana*, Goepp.; *h*, *Sphenopteris splendens*, Lx.

the young plants had the same general structure as the horse-tails, and that the gymnospermous features belonged to the later stages of the life of the individual plants. The group is represented to-day by one genus (*Equisetum*) and about 20 species. Its evolution

records a continuous decline from the Pennsylvanian period, when it was at its best.

Recent studies have shown that the graceful, slender plants with whorled leaves, referred to the genus *Sphenophyllum* (c, Fig. 397), formerly classed as calamites, should be made a class (Sphenophyllales, p. 685) by themselves. Their interest lies chiefly in the fact that while they have certain calamarian features, they have others possessed by lycopods. This is interpreted to mean that these two groups (calamarians and lycopods) were united with Sphenophyllales in a common ancestral form.[1] The stems were long, slender, and apparently weak, and a climbing habit has been inferred. The leaf structure suggests a shady habitat, perhaps one of undergrowth. The class, represented in the Devonian, had its climax in the middle Pennsylvanian, and continued into the Permian and possibly later.

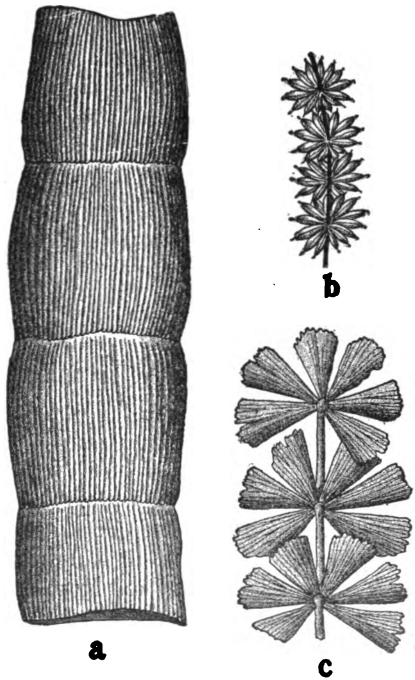



Fig. 397. Carboniferous Equisetales and Sphenophyllales: *a*, *Calamites cistii; b*, *Annularia sphenophylloides; c*, *Sphenophyllum longifolium.*

In size *Lycopods* (p. 685) were the master group of the Coal flora. They were represented by trees of large size which had the highest organization reached by the pteridophytes. From this high estate, they have since fallen to prostrate or weakly ascending plants of moss-like aspect (club mosses and ground pines.) The chief genera were *Lepidodendron* and *Sigillaria* (Fig. 395), of which the former was the earlier and simpler type. Both take their names from the leaf-scars (lepidos = scale, sigilla = seal) which the trunks retained (Figs. 398 and 399).

[1] Seward, Fossil Plants, p. 413; Scott, Studies in Fossil Botany, p. 494.

The trunks of some *lepidodendrons* were 100 feet in length. They were erect, and branched at a great height. The leaves were linear or needle-shaped, ranging up to six or seven inches in length, and set densely on the branches. Some of them had characteristics

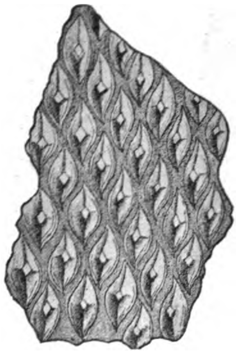


Fig. 398. Leaf markings of a lepidodendron.

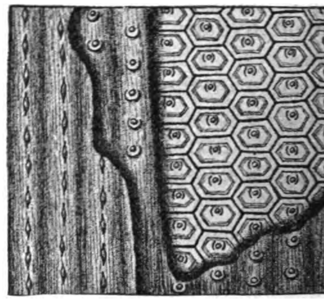


Fig. 399. Leaf markings of a sigillarian.

pointing in the direction of seeds, but it is not known that seed-producing plants sprang from them. More than 100 species of lepidodendrons have been described. They seem to have reached their climax early in the period, and nearly all had disappeared by its close.

The *sigillarians* differed from the lepidodendrons in being without many branches. They were perhaps the largest of the trees, their trunks reaching six feet in diameter, and 100 feet or more in height. The stems were densely clothed with erect, rigid, linear leaves. They were more abundant than lepidodendrons before the close of the period, but were on the wane at its close.

The group is essentially Pennsylvanian but initial forms lived in the Devonian and Lower Carboniferous, and a few survived to the Permian.

**Cordaitales.** One of the characteristic trees of the period was *Cordaites*, which belonged to a remarkable family (now extinct) of gymnosperms. The trees were 90 feet or more in height, and rather slender. The wood was of the coniferous type, covered, as in so many other plants of the period, by a thick bark. The trunks had a large pith. The leaves were parallel veined, suggestive of monocotyls of the yucca type, and in some cases attained a length of six

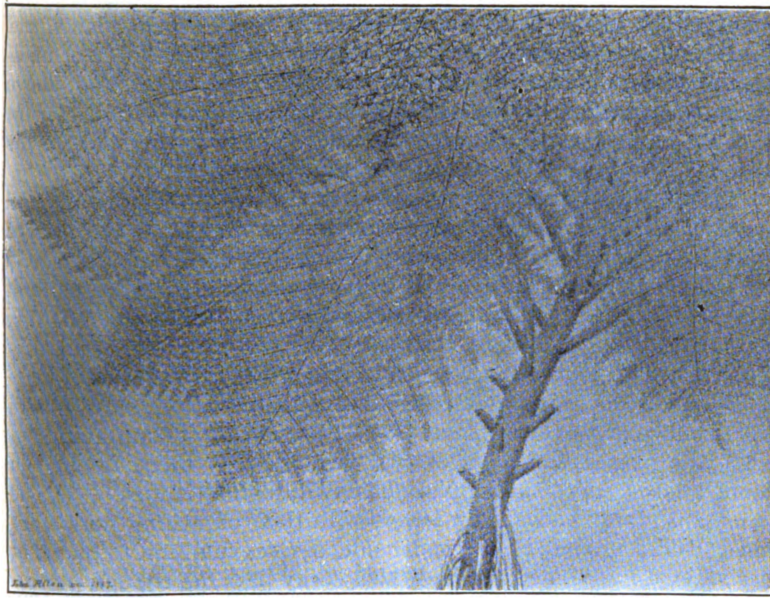


Fig. 400. One of the Cycadofilices, *Lyginodendron oldhamia.* (Restoration by D. H. Scott and J. Allen.)

feet and a width of six inches. They are preserved in great abundance, and make up a large part of some beds of coal. In one form, the leaf had a distinctly fleshy character, as if adapted to xerophytic (dry) life. The floral organs were peculiar to the family, and have been worked out with marvelous success, even the structure of the pollen having been determined.

Conifers have not been found in the Pennsylvanian rocks, but the vegetation of the uplands, where conifers probably would have lived, is not known.

### *Climatic Implications of the Coal-plants*

What suggestions do the Coal-plants give relative to the atmospheric conditions under which they grew? Two partly antagonistic views relative to these conditions have been held. The one regards the beds of coal as evidence of a very luxuriant growth of vegetation, which in turn has been thought to imply a warm, moist atmosphere, heavily charged with carbon dioxide. The great size of

many of the trees, the succulent nature of many of the plants, and the abundance of aërial roots, are appealed to as evidence of mildness of climate, while the absence of rings in the wood, and, above all, the distribution of similar floras through diverse latitudes, point strongly to an equable climate, especially in the earlier part of the period. It is clear that this view has much support.

The alternative view postulates less warmth and moisture, and more diversity; in other words, a nearer approach to the present conditions. It assumes, however, a somewhat higher percentage of carbon dioxide than now, and a climate milder and more uniform than that of to-day. The basis of this view is found in the following considerations: (1) Great thicknesses of coal do not necessarily imply rapid accumulation, any more than great thicknesses of limestone do. Given favorable conditions of preservation, slow growth will produce great thicknesses. (2) At present the accumulation of peat, the nearest analogue of coal formation, is most favored in cool climates, and is taking place chiefly in high latitudes. (3) The dominant plants had narrow leaves with their breathing pores confined to deep furrows on the under side, devices common to plants of dry regions. (4) The trees had thick corky bark, as though protection from external conditions was needed.

The thickness of the bark, and the form and structure of the leaves, give a xerophytic aspect to the overgrowth made up of lepidodendrons, sigillarias, calamites, and cordaites. This is not the case with the undergrowth, but this would not be expected of shaded plants. The force of the inference from the xerophytic aspect of the overgrowth is much weakened by the fact that the vegetation of undrained swamps and bogs has many xerophytic features. It is clear that a more critical study of the problem is needed before a final conclusion concerning the climate of the period is reached.

### *Land Animals*

So far as the evolution of air-breathing vertebrates is concerned, this is one of the most important periods in geological history.[1] Amphibians, insects, spiders, scorpions, and myriapods, lived on the land at this time. The amphibians are perhaps of chief interest, for they were the first land vertebrates.

**The rise of amphibians.** Tracks attributed to amphibians are found in the Devonian and Mississippian, but in neither of these

[1] Williston. *Faunal Relations of Early Vertebrates*, Jour. Geol., Vol. xvii, p. 389.

systems have bones of these animals been found in America, and only imperfect ones in Europe. Fossils of amphibians first appear in abundance in the later Coal Measures, and in such variety as to imply a long antecedent existence. Most of them were rather primitive in structure, but they were genuine amphibians, not transition types. All of them seem to have had elongate forms, and their heads were well roofed over by the bony plates of the skull. On account of this last feature they are called *stegocephalians* (roofheaded). Some of them have also been named *labyrinthodonts*, from the intricate infolding of the dentine of their teeth. Labyrinthodonts were doubtless the largest amphibia of the period, some of their skulls reaching a length of half a meter.

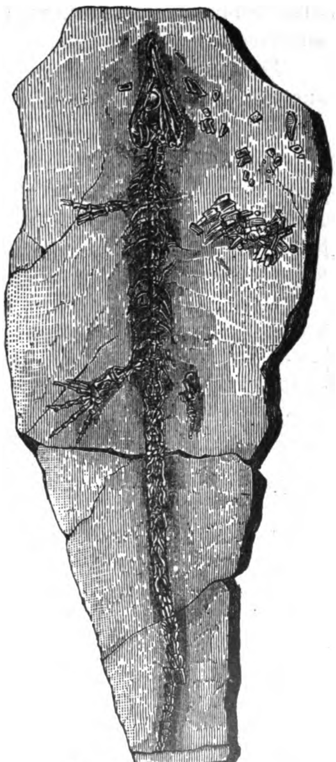


Fig. 401. A CARBONIFEROUS AMPHIBIAN; *Lepterpeton dobbsi* Huxley. A microsaurian from Kilkenny, Ireland, about 3/5 natural size. (Zittel.)

The amphibia varied in length and strength of limb, in agility, ability to climb, etc. The elongation of their bodies involved a notable multiplication of the vertebræ, one form having no less than 150. Before the close of the period, probably some of them lived on dry land where fleetness, rather than protective armor, preserved them from their enemies. Others were limbless and snake-like, crawling reptiles in everything except certain technical details of their palates.

One branch of the amphibia which reached its highest development in the Permian is supposed by some paleontologists to be the ancestral stock from which mammals arose. The other branch, which included the labyrinthodonts, is the only group of Pennsylvanian air-breathing vertebrates which left no descendants.

Not much is known of the habits of the amphibia, but from their

teeth it is inferred that they were predaceous. In Nova Scotia, Dawson took thirteen skeletons of amphibians from a single sigillarian stump. Since land shells and myriapods are found in stumps with the amphibian skeletons, it has been inferred that some of the amphibians were climbers, and lived on mollusks, myriapods, and similar land life.

The amphibians of different continents were so similar as to suggest great freedom of communication and migration, but free

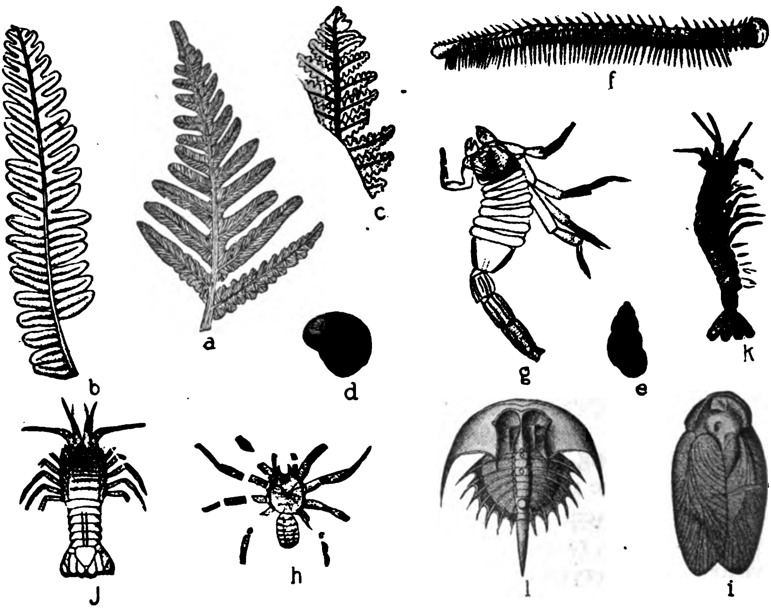



Fig. 402. Carboniferous Terrestrial and Fresh-water Life. *Plants:* *a*, *Callipteridium mansfieldi* Lesq., *b* and *c*, *Callipteridium membranaceum* Lesq., species of ferns. Land shells: *d*, *Zonites priscus* Carp., *e*, *Pupa vermilionensis* Bradley. These land snails have been referred to genera living at the present time, and although this reference may eventually prove to be incorrect, they are at least close relatives of recent genera. Insects, etc.: *f*, *Euphoberia armigera* M. and W., a Carboniferous myriapod or thousand-legged worm; *g*, *Eoscorpius carbonarius* M. and W., a scorpion very similar in type to living forms; *h*, *Arthrolycosa antiqua* Harger, a spider more primitive than recent forms as seen by the segmentation of the abdomen; *i*, *Progonoblattina columbiana* Scudd., one of the allies of the modern cockroaches which were the most conspicuous members of the Carboniferous insect fauna. Crustacea: *j*, *Anthrapalæmon gracilis* M. and W., *k*, *Palæocaris typus* M. and W., types of crustaceans found in the Mazon Creek nodules; *l*, *Prestwichia danæ* M. and W., an early ally of the modern horseshoe crab. (Weller.)

intercontinental migration seems to have come to an end by the close of the period.

**Insects.** Hundreds of species of insects have been identified from the Coal Measures. They were, for the most part, rather primitive types. *Orthopters* (cockroaches, *i*, Fig. 402, locusts, crickets, etc.) were greatly in the lead, followed by *neuropters* (represented by ancestral mayflies). These two orders include about 90 per cent of the known insects. *Hemipters* (bugs), which had appeared earlier, and possibly *coleopters* (beetles) were present, but no fossils of bees, butterflies, or moths have been found, and there is little probability that they existed, since flowering plants, on which they depend, had not yet appeared. There is no record of flies. The evolution of insects was therefore one-sided. Curious forms were developed within the orders which lived, and remarkable sizes were attained, spreads of wing of a foot or more being reported.

*Spiders* and *myriapods* (Fig. 402) were plentiful, and several species of *land snails* (*d* and *e*) have been identified. The amount of carbon dioxide in the atmosphere could not have exceeded that compatible with this varied assemblage of air-breathing life.

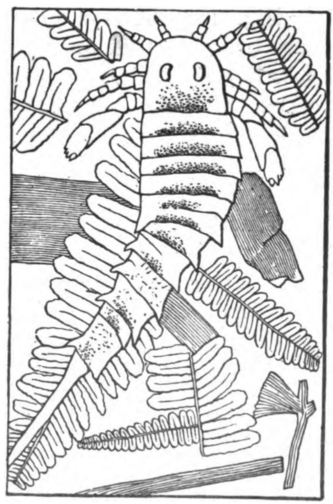


Fig. 403. Natural association of *Eurypterus mansfieldi* with ferns and calamites. (From Dana after Hall.)

### *Fresh-water Life*

Besides fresh-water plants, the life of land waters appears to have consisted of fishes, mollusks, crustaceans, and doubtless of many other forms. Aside from the development of the fresh-water fish and amphibia, perhaps the most suggestive feature was the association of the arthropods with other forms of life. Eurypterids (Fig. 403) were still in existence, and their relics are so intimately associated with ferns, calamites, insects, spiders, and scorpions as to leave no reasonable doubt that they were fresh-water forms. There were also crustaceans resembling crayfish, and others of shrimp-like appearance.

## *Marine Life*

Two phases of sea life are worthy of note, (1) that which occupied the shallow water, which, in the form of estuaries, lagoons, and shoals, crept in and out on the borders of the continent as the relations of land and sea oscillated, and (2) the life of the more open seas. No doubt this distinction had existed always, but it had not before reached equal importance. In the coal regions of this period, a large part of the fossils are of shallow water types. In shallow water, where sandy and muddy flats prevailed, pelecypods and gastropods, together with certain fishes, predominated, while in the more open seas the brachiopods, cephalopods, and clear-water types were more plentiful. During the period, there was progress among the fishes in adaptation to swift movement, and in shapeliness of form.

It is difficult to tell which of them were marine, which fresh water, and which common to salt and fresh water. It is clear that much the larger number of those in the American Coal Measures lived in fresh water; whether also in salt water is uncertain.

Fig. 404 shows a group of Pennsylvanian marine fossils. It may be noted that ancient and relatively modern types of *cephalopods* lived together, the former represented by straight, plain, small orthoceratites (*z*, Fig. 404), and the latter by closely coiled goniatites (*zz*), with curved sutures. The former were about to take their final leave, and the goniatites were about to evolve into ammonites, the dominant type of the Mesozoic era. *Brachiopods* were abundant, and their general facies was like that of the later Mississippian. Some species range not only through northern America and Eurasia, but into the Orient and Australasia. A close relation between several American and Russian crinoids implies intermigration. *Cystoids* and *blastoids* were gone, and other forms of echinoderms were rare. *Trilobites*, which commanded foremost attention at the opening of the Paleozoic, are now almost at the point of disappearance. The last representative of the group had the chaste beauty of its early ancestors. *Bryozoans* were not uncommon, but the peculiar devices for support illustrated in *Archimedes* and *Lyropora* of the preceding period were abandoned. *Protozoans* were represented widely by a little foraminiferal shell (*Fusulina secalicus*, *b*, Fig. 404), which had about the size and form of a grain of wheat. Its abundance gives character to the Fusulina limestone which occurs in America, Europe, and Asia. *Corals* were rare, as might be expected under the conditions of the time.

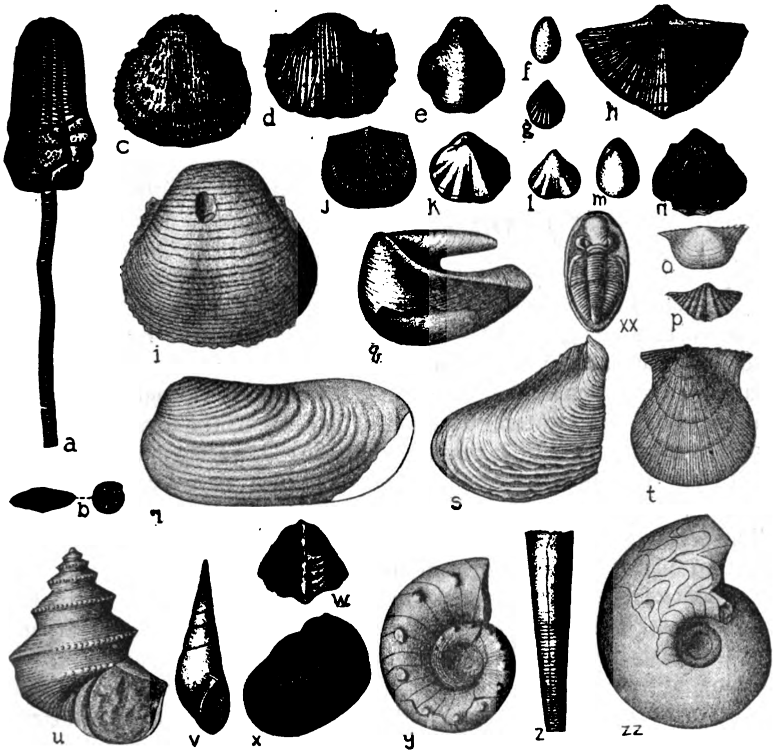



Fig. 404. PENNSYLVANIAN MARINE FAUNA: *a*, *Eupachycrinus magister* M. and G., a crinoid with biserial arms; *b*, *Fusulina secalicus* Say, a foraminifer shell that in places makes up considerable beds of limestone. *c-p*, brachiopods: *c*, *Productus nebrascensis* Owen; *d*, *Productus costatus* Sow.; *e*, *Seminula argentea* (Shep.), a spire-bearing common Carboniferous species; *f*, *Lingula umbonata* Cox, a representative of a genus which persisted from the Cambrian to recent times; *g*, *Hustedia mormoni* (Marc.); *h*, *Spirifer cameratus* Mort., a characteristic member of the Pennsylvanian fauna; *i*, *Productus symmetricus* McCh.; *j*, *Derbyia crassa* (M. and H.); *k*, *Enteletes hemiplicata* (Hall); *l*, *Pugnax uta* (Marc.); *m*, *Dielasma bovidens* (Mort.); *n*, *Meekella striatocostata* (Cox); *o*, *Chonetes granulifera* Owen; *p*, *Spiriferina kentuckiensis* (Shum.). *r*, *Allorisma subcuneata* M. and H. *q-t*, pelecypods: *q*, *Monopteria longispina* Cox; *s*, *Myalina recurvirostris* M. and W.; *t*, *Aviculopecten occidentalis* Shum. *u-x*, gastropods: *u*, *Worthenia tabulata* (Con.); *v*, *Meekospira peracuta* (M. and W.); *w*, *Bellerophon percarinatus* Con.; *x*, *Naticopsis altonensis* (McCh.); *y*, *z*, and *zz*, cephalopods: *y*, *Temnocheilus forbesianus* (McCh.); *z*, *Orthoceras cribrosum* Gein.; *zz*, *Paralegoceras newsomi* Smith; *xx*, *Phillipsia major* Shum.

***Map work.*** No reference to map work has been made since that at the close of the chapter on the Ordovician, p. 387. Experience has shown that if the principles of stratigraphy, as illustrated by the Cambrian system, are well developed, further map work may be deferred to about this point. See laboratory manual already referred to (p. 387), exercise IX.

# CHAPTER XXI

## THE PERMIAN PERIOD

### FORMATIONS AND PHYSICAL HISTORY

At the close of the Pennsylvanian period much of the central and eastern parts of the United States became dry land, and the sea-covered area in the west was greatly restricted. The area of land was perhaps as large as at any time since the beginning of the Paleozoic. The waters which still lay upon the continent were partly in the form of lakes and inland seas, and partly connected with the open ocean; but the areas which the sea overspread at the beginning of the period were largely abandoned before its close. These changes in geography reflected themselves both in the distribution of the Permian formations and in their character.

**East of the Mississippi.** During the earlier part of the period fresh-water sedimentation continued much as before in some parts of the east (parts of Pennsylvania, West Virginia, Maryland, and Ohio), and with the commoner sorts of sedimentary rocks there is some coal. There, and in and about Nova Scotia, non-marine Permian strata rest on Pennsylvanian beds in such a way as to show that sedimentation was not seriously interrupted. The systems are separated on the basis of fossils. Recently, a conglomerate formation (the *Roxbury*) of Eastern Massachusetts has been interpreted as of glacial origin. This origin suggests its reference to the Permian[1].

**West of the Mississippi.** West of the Mississippi the system is better developed, being partly marine and partly non-marine. In Kansas and Nebraska its lower part is marine, and the Permian of these states is probably continued northwestward to Wyoming and South Dakota. The marine Permian of Kansas is overlain by beds containing gypsum and salt, and possessing other features which show that the open sea of the region was succeeded by dissevered remnants, or by salt lakes whose supply of fresh water was exceeded by evaporation. With the saline and gypsiferous deposits, and above them, are the "Red Beds," many of which are Permian.

[1] Sayles, Bull. Mus. Comp. Zool. Vol. LVI. (Geol. Ser. X) pp. 141-170, and Science, Vol. 32 (1910) p. 723.

Some of the Red Beds in western Texas, New Mexico, and elsewhere are perhaps later than Permian, and some in Oklahoma, Kansas, Colorado, and perhaps elsewhere, are older.

In the Staked Plains of Texas the system has its greatest development. The oldest part (*Wichita* formation) is partly of marine and partly of fresh-water origin. The Middle Permian (*Clear Fork* limestone) is of marine origin, and overlaps the Lower. The Upper Permian (*Double Mountain* formation) indicates a reversal of conditions, for much of Texas was again cut off from the ocean, and converted into an inland sea or seas, in which the phases of deposition common to such bodies of water took place. Occasional beds of limestone with marine fossils point to occasional incursions of the sea, while deposits of salt and gypsum point with equal clearness to its absence, or to restricted connections, and to aridity of climate.

Throughout much of the area west of the Rocky Mountains the Permian has not been differentiated. There is, in places, conformity between the Carboniferous below and the beds classed as Trias above, suggesting the presence of unseparated Permian between. In northern Arizona and in southwestern Colorado and perhaps at other points, there is an unconformity at the top of the Permian. The Permian system may have been continuous once from Texas to the Great Basin, by way of New Mexico and Arizona; but if so, the continuity of the beds has been interrupted by erosion. A very considerable thickness of marine Permian (3,800 feet) is reported from Utah. Many Permian deposits of the far west, and some of those in the longitude of Texas and Kansas, are red. This color characterizes so many formations known to have been made in inclosed basins that the connection can hardly be accidental.

**Thickness.** In the Appalachian region, the Lower Permian beds, sandstone and shale with thin seams of coal, have a thickness of about 1,000 feet. The Upper Permian is wanting. In Kansas the thickness is twice as great, while in Texas it reaches 7,000 feet.

**Correlation.** In the region east of the Mississippi, the Permian is so closely associated with the Coal Measures that the two were formerly classed together, the Permian being called Upper Barren Coal Measures. Were this region only considered, this classification would appear to be satisfactory. In the western part of the continent the separation of the Permian from the Carboniferous will probably prove to be more distinct, when details have been worked out, and its relation with the Trias close. The Permian

period is best looked upon as a transition period from the Carboniferous to the Trias, and so from the Paleozoic to the Mesozoic. Its close relationship to the underlying system in some places, and to the overlying system in others, is therefore to be expected.

### *Foreign Permian*

*Europe.* In Europe, as in America, the Carboniferous period was brought to a close by very considerable changes, for much of the area which had been receiving deposits during that period was exposed to erosion at its close. Subsequently, much of the same surface was again the site of deposition, partly from fresh and partly from salt waters. The system is here much more distinct from the Carboniferous than in eastern North America.

In western and central Europe, the *Lower Permian* (*Rothliegende*) consists of a series of clastic formations, together with a large amount of igneous rock, in the form of lava-sheets, dikes, and pyroclastic material. The formations and their fossils show that much of the sediment was accumulated in inland seas, and in salt and fresh lakes. Gypsum, salt, and a meager fauna of dwarfed and stunted species are among its distinctive marks. But the sea sometimes had access to the inland areas of sedimentation, as fossils show. The shallow-water or subaërial origin of much of the Permian is shown by the sun-cracks, rain-pittings, ripple-marks, tracks of terrestrial and amphibious animals, etc. In keeping with the conditions of its origin the Rothliegende contains some coal.

Especial interest attaches to the conglomerates and breccias, because of their likeness to glacial drift. The conglomerate is widespread, and in places contains bowlders which have been transported great distances; but its glacial origin has not been proved.

The *Upper Permian* of western and central Europe (the *Zechstein*) is unlike the Lower in several important respects. It contains much more limestone and dolomite, but neither coal, igneous rock, nor, except at its very base, conglomerate. From the stunted aspect of the fossils, and from the association of the dolomite with gypsum, salt, etc., it has been thought that the limestone and dolomite may be largely chemical precipitates. Some parts of the Permian are, however, of marine origin.

The Upper Permian of central and western Europe contains the thickest mass of salt known. Near Berlin, one body of salt has been penetrated about 4,000 feet, without reaching its bottom. It

may be doubted, however, whether there is a salt *layer* of this thickness. Besides common salt, salts of potash and magnesium are present locally in such quantity as to be commercially valuable. With the exception of saltpetre, the world's supply comes from these beds.

The system underlies the larger part of Russia (in Europe), and appears at the surface over a large area in the southeastern part of

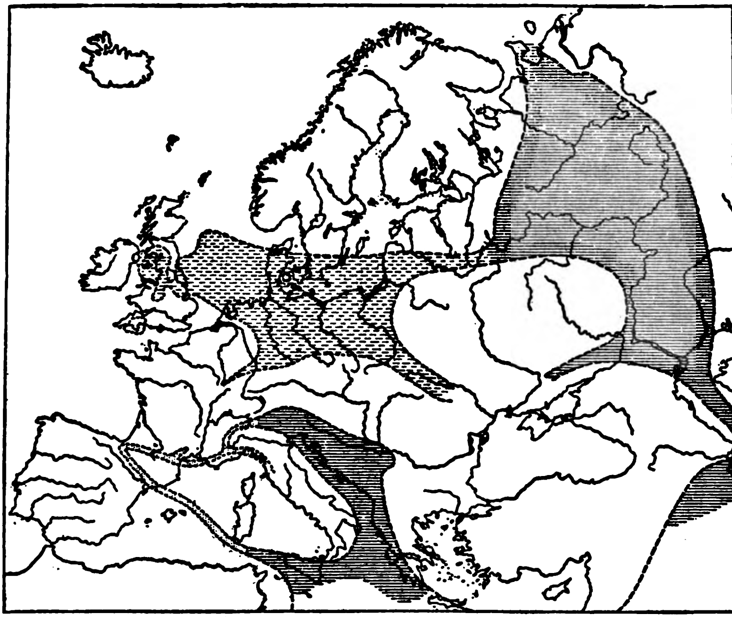


Fig. 405. Sketch map of Europe during the later part of the Permian period. The lines indicate areas of marine deposition, the broken lines areas of lagoon deposits. (After De Lapparent.)

that country. Here and in southern Europe generally the Permian is conformable on the Carboniferous, and is partly marine and partly non-marine. In Russia it contains salt, gypsum, etc., and also, at some horizons, marine fossils.

**Other continents.** In other parts of the world the Permian is widely developed. In countries about the Indian Ocean, there is a less distinct break between the Carboniferous and Triassic systems than in Europe, and locally at least, the Permian seems to bridge the interval completely.

*Permian glacial formations*. The most remarkable fact about the Permian as a whole is that it includes formations of *glacial origin*, and that these occur down to and even within the tropics. Such formations are found in all the continents which have large areas in low latitudes.

In *Australia*, strata of Permian glacial drift are interbedded with marine formations and coal beds, the aggregate thickness of the whole being not less than 2,000 feet. The recurrence of the bowlder beds points to the repeated recurrence of glacial conditions, and the great thickness both of clastic beds and of the many included coal beds points to the great duration of the period through which the several glacial epochs were distributed.

Counting Tasmania, the glaciation of Australia had a known range of nearly 22° in latitude, and about 35° in longitude, though it is perhaps not probable that all the area within these limits was glaciated. The glacial formations are known chiefly at low levels, descending in some places nearly to the sea. Not only is the altitude of the region low now, but it was probably low during glaciation, as shown by the interbedding of glacial and marine formations.

The fossils of the marine beds associated with the glacial deposits are similar to those of the Carboniferous (Pennsylvanian) period elsewhere, but the plants of the associated coal have a Triassic facies. Permian fish remains are found above all the bowlder beds, suggesting that the glacial conditions were over before the end of the Permian. The plant fossils therefore indicate that the period of glaciation was late Permian or early Triassic; the marine fossils, that it was late Carboniferous or early Permian.

In *India*, too, there are glacial formations (*Talchir conglomerate*) of about the same age, with fossil plants like those of Australia in associated beds. The bed on which the glacial formations rest is in some places striated and roche-moutonnéed, as beneath modern glacial deposits. These formations are even more remarkable than those of Australia, for they reach several degrees within the Tropic of Cancer (to Lat. 18°). Similar formations appear farther north in India where marine Permian beds overlie the glacial series.

In *South Africa* many of the bowlders of the glacial beds (*Dwyka conglomerate*) are striated, and the bed on which the glacial conglomerate rests shows indisputable marks of ice action in many places. The glacial beds are believed to have extended to 26° 40′. In *South America* glacial conglomerates also are present in the

southern part of Brazil, and in Argentina. The associated coal formations carry the same flora (glossopteris flora) as in the other continents.

In the northern hemisphere the glaciation is known to have extended from latitude 18° to about 35°, and in the southern, from latitude 21° to 35°. In an equatorial zone about 40° in width, glaciation has not been discovered. The glaciation can hardly be said to be limited in longitude. Glacial conditions must, therefore, have prevailed about the borders of an area many times as large as that covered by ice in the northern hemisphere during the Pleistocene glacial period.

The marked likeness of the floras associated with the glacial deposits in these four continents is evidence that there was land connection between them at the time of glaciation. The age of the glacial beds is not absolutely established, for the Carboniferous and Permian are not clearly differentiated in the regions where they occur. Perhaps the best judgment that can be formed now is that the Paleozoic glaciation culminated in the early part of the Permian period.

### *Close of the Paleozoic Era*

The close of the Paleozoic era was marked by much more considerable geographic changes than the close of any period since the Proterozoic, though they may be said to have been in progress during the Permian period, rather than to have occurred at its close. The more important changes in North America, which were far advanced by the close of the Paleozoic, were (1) the development of the Appalachian mountain system at the western border of Appalachia; (2) the deformation of the surface of Appalachia; (3) the development of the Ouachita Mountains; (4) the final conversion of most of the area between the Great Plains and Appalachia from an area of deposition to one of erosion; and (5) the restriction of the area of sedimentation in the western interior.

Such extensive geographic changes, involving the conversion of extensive areas from sea bottom into land, must have caused profound changes in the circulation of ocean waters, in the climate of many localities, and in the distribution of life.

## LIFE

The life of the Permian must be interpreted in connection with the extraordinary physical conditions which formed its environ-

ment. The salient facts in connection with the physical conditions of the period were *glaciation* and *aridity*. In view of these facts, certain questions relative to the life arise: (1) Did it possess such powers of adaptation as to meet its extraordinary environment by adjusting itself to it? (2) Was it destroyed co-extensively with the changes in environment? (3) Did it elude adverse conditions by migrating from one area to another as the adverse conditions shifted (hypothetically)? (4) Did its composite experience embrace all these alternatives, and if so, what measure of each?

In the early days of geology it was commonly held that a complete destruction of all things living on the face of the earth attended the close of the Paleozoic era, and that a re-creation followed; for at that time, no Paleozoic species was known to have lived on into the following era. But it is now known that some species bridged the interval, and it is believed that others underwent modifications which enabled them to live. The progress of investigation is bringing more and more evidence of this kind to light. Not only this, but the compensating effects of the strenuous conditions in calling into play the powers of adaptation and resistance of the organisms are coming to be recognized. Notwithstanding all this, it appears that the life of the period was greatly impoverished. A census made not many years ago gave the known animal species of the Carboniferous period as 10,000, while those of the Permian period were only 300. A census to-day would probably increase the Permian ratio, but the contrast would still be great.

**Plants.** The change in the vegetation was rather marked in America, though not, at the outset, radical. Of the 107 species of plants recorded from the lowest Permian beds of West Virginia and Pennsylvania, 22 are found in the Coal Measures below. This and other similar facts show that a rather profound change was in progress, but that it was not abrupt. But a small part of the total floral changes of the Permian appears in the American record, as now known; but the nature of the early change is indicated distinctly. *Lepidodendrons* disappeared, *Sigillaria* became rare, and *Calamites* were greatly reduced. The general features of the fern group remained much as in the preceding period, but most of the species and many of the genera were new. *Cordaites* continued, and initial forms of *Ginkgos* appeared, giving to the flora a Mesozoic cast.

In Europe Carboniferous types declined as the period advanced, and the general aspect of the flora was that of poverty. Of the new

types which appeared, one is a supposed forerunner of the group to which the giant sequoia and the bald cypress belong.

The most remarkable fact connected with the plant life of the period was the evolution of the *Glossopteris* (tongue-fern), or Gangamopteris, flora in the southern hemisphere, and its migration into

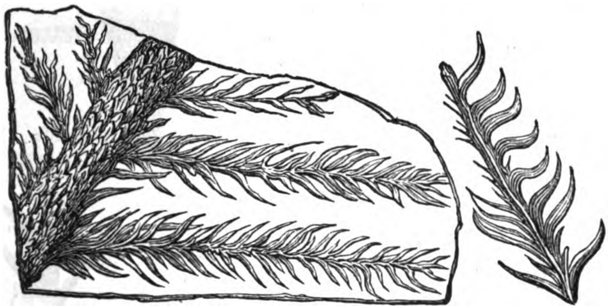


Fig. 406. *Walchia piniformis*, a Permian conifer of Europe.

the northern. This flora suggests that it was evolved to meet the adversities of climate in and about the glaciated regions. Developed amid adverse surroundings, if not under adverse conditions, the flora not only took on a resistant aspect in simple outlines and compact forms, but gave evidence of its vitality by spreading northward into east Africa, Asia, and Europe. It reached northern Russia in the later part of the Permian period, and was there associated with forms typical of the European Permian flora. It is found also in Brazil and Argentina. Its vitality is further shown in that its descendants became a dominant feature in the Mesozoic floras that followed.

**Land animals.** *Amphibians*, which reached their climax in the later portion of the Pennsylvanian period, were still abundant in the early Permian; but before the end of the period they were overshadowed by the reptiles, which were doubtless their descendants.

While *reptiles*[1] probably began to differentiate from amphibians earlier, the oldest certain relics of them go back but little beyond the beginning of the Permian; but before the close of the period the group was large and complex. At least three distinct phyla existed. One of them (*Pelycosauria*), pronouncedly reptilian in character,

[1] Williston, Faunal Relations of Early Vertebrates, Jour. Geol., Vol. XVII, 1909.

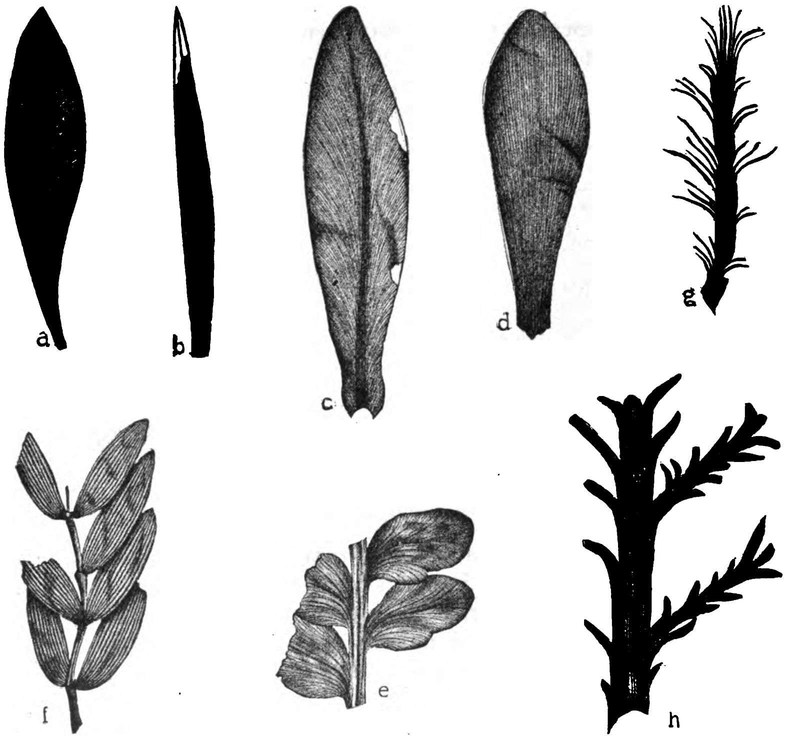



Fig. 407. Representative types of the Glossopteris flora. *a*, *Glossopteris communis*, Fstm.; *b*, *G. angustifolia*, Bgt.; *c*, *Gangamopteris cyclopteroides*, Fstm.; *d*, *Noeggerathiopsis hislop*, Bunb.; *e*, *Neuropteris valida*, Fstm.; *f*, *Schizoneura gondwanensis*, Fstm.; *g*, *Phyllotheca indica*, Bunb.; *h*, *Voltzia heterophylla*, Bgt.

had branched off before the close of the Pennsylvanian period (Fig. 408); another (*Cotylosauria*) included crawling reptiles with large heads, short tails, powerful and short limbs, whose nearest and yet rather remote relatives (*Pareiasaurus*) are found in South Africa; the third (*Therapsida*) included the anomodonts and theriodonts, reptiles allied to the pelycosaurs, but more highly specialized. The American forms were probably derived from the same stock as their African allies, but the types in the two continents had, as a result of long isolation, become somewhat distinct. Some of the African reptiles are of peculiar interest because of the mammalian aspect of their skulls, teeth, and other parts of their skeletons.

These were especially abundant in South Africa (Karroo beds[1]), but they have been found also in Europe. The rapid and diverse deployment of the early reptiles in a period of general life-impoverishment is not a little remarkable, but as the reptiles were air

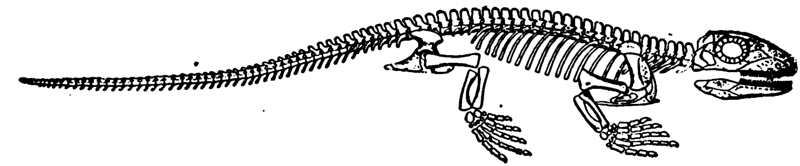


Fig. 408. *Palæohatteria longicaudata*, from the lower Permian of Germany, about ¼ natural size. (Restoration by J. H. McGregor.)

breathers, the key to their rise may lie in a more oxygenated atmosphere, a point to which we shall return.

The Permian of Texas and Oklahoma affords the richest Permian vertebrate fauna now known. In contrast with the verte-

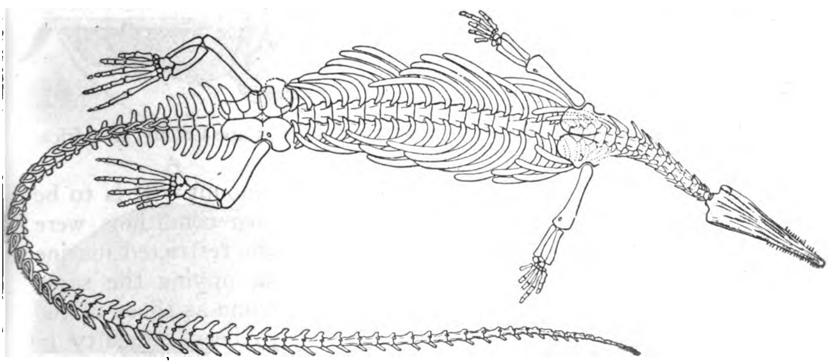


Fig. 409. *Stereosternum tumidum*, from Brazil, about ¼ natural size. (Restoration by McGregor.)

brate fauna of the Pennsylvanian system, this fauna is so unlike the Permian faunas of other continents as to imply that land animals did not migrate between North America and other continents. This isolation seems to have lasted from the later part of the preceding period well into the Triassic.

The Permian record of terrestrial invertebrates is poor.

[1] The Karroo beds, so wonderfully rich in significant vertebrate remains, are regarded as Permian in part, and Triassic in part. Broom, *Geol. of Cape Colony*, 1905, pp. 228–249.

**Fresh-water life.** Besides the amphibians and some of the reptiles which constituted, in a sense, a portion of the fresh-water life, fishes were abundant. On the whole they had a rather modern aspect. There were fresh-water mollusks, some of which resembled unios.

**Marine life.** The withdrawal of the epicontinental seas from considerable portions of the continents reduced the area available

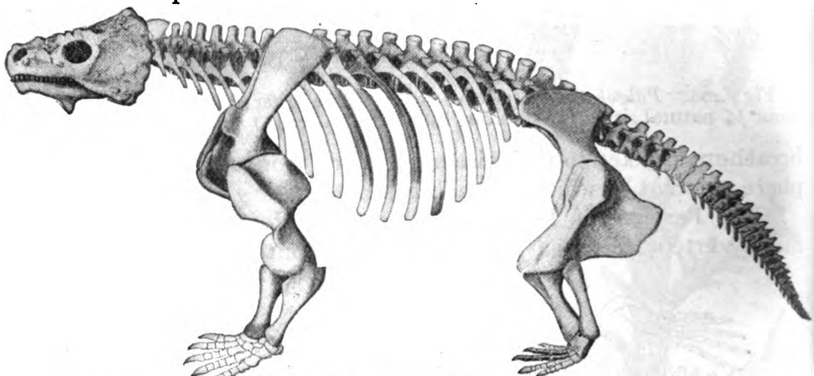


Fig. 410. *Pareiasaurus serridens*, Karroo formation, Cape Colony, S. Africa; about 1/25 natural size. (After Broom.)

for shallow-water sea life, and so reduced its amount. It is to be noted that this reduction came at a time when conditions were unfavorable for land life. In North America the restricted marine faunas were lineal descendants of ancestors occupying the same area. At first, many of the species were the same as those of the preceding period, and hence there has always been difficulty in drawing a dividing line between the systems. The known species of the marine Permian of the Great Plains are only about 70, and of these about half are *pelecypods*.

The increasing complexity of the sutures of the coiled *cephalopods* has been noted in previous chapters. By the close of the Permian, the complexity (Fig. 411), foreshadowed that of the Mesozoic ammonites, though older types (goniatites and nautiloids) still lived. The ancient straight form (Orthoceras, *f*, Fig. 411), was in the last stage of its long career. The contrast between the disappearing straight type, in its depauperate form, and the robust youthful ammonites (*a* and *b*, Fig. 411), about to become a ruling dynasty, is marked.

**Retreatal tracts of marine life.** As in previous transition epochs when epicontinental waters were largely withdrawn, the marine faunas found special refuge in certain embayments or border tracts which, in connection with the coastal belts, permitted them

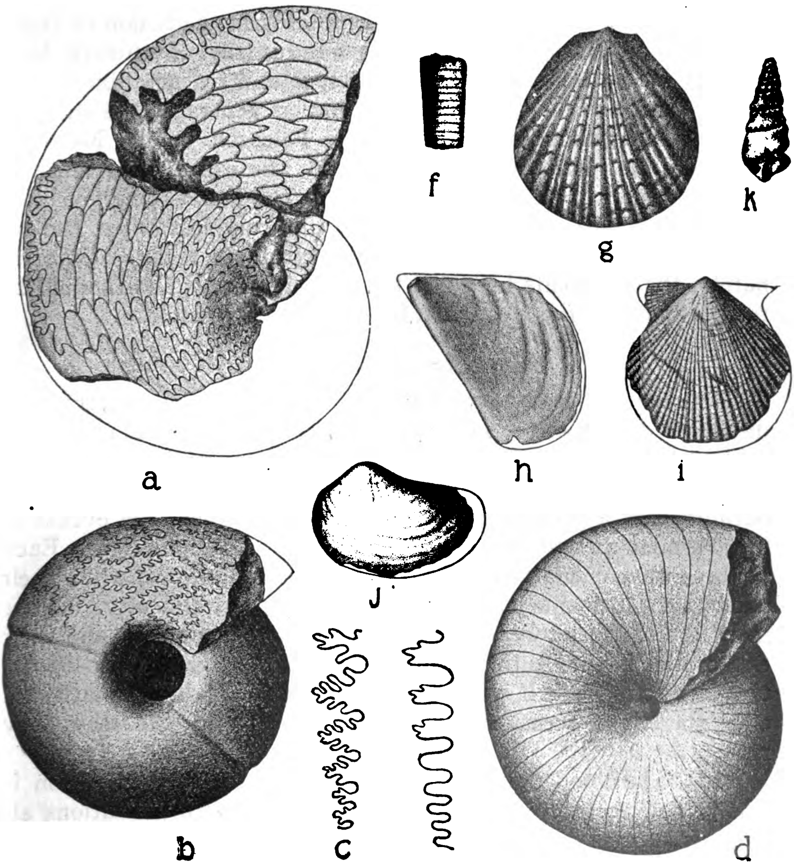



Fig. 411. Marine permian fossils. *a-f*, Cephalopods: *a*, *Medlicottia copei* White; *b* and *c*, *Waagenoceras cumminsi* White; *d* and *e*, *Popanoceras walcotti* White, three forms of ammonoids with sutures more complicated than in earlier forms; *f*, *Orthoceras rushensis* McCh., one of the last of the orthoceratites. *g-j*, Pelecypods: *g*, *Pseudomonotis hawni* (M. and W.); *h*, *Myalina permiana* (Swall.); *i*, *Aviculopecten occidentalis* (Shum.); *j*, *Sedgwickia topekaensis* (Shum.). *k*, *Murchisonia* sp., a gastropod.

to re-form themselves, regenerate their species, and prepare for a succeeding invasion of the continental areas. On the American continent, the St. Lawrence embayment had done repeated duty in this line; but there is no specific evidence that it participated notably in the Permo-Triassic transition. The border of the Gulf of Mexico, the Mediterranean tract, notably in the region of Sicily and southeast Europe, and the Ganges-Indus tract of southern Asia, seem to have been special areas of refuge and regeneration at this time. Here and on the continental borders generally, the shallow-water marine faunas passed from the Paleozoic to the Mesozoic phases. The restriction, compared with the expansional stage of the Mississippian period, was great; but the faunas emerged with new species born in adversity, ready for conquest when the re-advancing seas should give them an expanding realm. Unfortunately, the sediments in which this transition of faunas should be recorded are, for the most part, buried and inaccessible.

### PROBLEMS OF THE PERMIAN

Between the marvelous deployment of glaciation, a strangely dispersed deposition of salt and gypsum, an extraordinary development of red beds, a decided change in terrestrial vegetation, a great depletion of marine life, a remarkable shifting of geographic outlines, and a pronounced stage of crustal folding, the events of the Permian period constitute a climacteric combination. Each of these phenomena brings its own unsolved questions, while their combination presents a series of problems of great difficulty. These marked phenomena were probably related to one another, and their explanation is quite sure to be found in a common group of co-operative factors. While it is too much to hope for a full explanation at once, there is no occasion to blink the facts or evade the issues they raise.

It is to be noted that none of the factors in this combination is wholly new to geological history. There had been glaciations almost as strange in early Cambrian times; there had been signs of unusual aridity in the salt and gypsum deposits of the Silurian; there had been red beds in the Devonian and Keweenawan; there had been marked restrictions of life, as at the close of the Ordovician; there had been extensive geographic changes in earlier Paleozoic periods; and there had been foldings of surpassing intensity in Archean and Proterozoic times. The peculiarity of the Permian

was the complexity of the combination, and the extent of glaciation and aridity.

The chronological setting of the combination lends some advantages to its study. It lies in the midst of geologic history, with periods of climatic uniformity and polar geniality both before and after. No appeal can be taken to a supposed final cooling of the earth, or to any senile condition. It was an episode in the midst of a long history, and its problems must be faced with this setting in mind.

# THE MESOZOIC ERA

## CHAPTER XXII

## THE TRIASSIC PERIOD

### FORMATIONS AND PHYSICAL HISTORY

When the sea was excluded from the area between the growing Appalachians and the Great Plains at the close of the Paleozoic, *Appalachia* appears to have suffered deformation, one result of which was the development of elongate troughs upon its surface, roughly parallel to the present coast. These troughs became the sites of deposition, and the sediments laid down in them constitute the only representative of the Triassic system in the eastern part of the continent. The open sea seems to have been excluded from the ***western interior*** by the beginning of the Triassic period, though sedimentation was in progress over considerable areas between the meridians of 100° and 113°. Some of these areas appear to have been sites of salt seas and some of fresh lakes, while still others were probably without standing water. Between the meridians named, many areas of relatively high land probably interrupted the continuity of the areas of sedimentation. On the ***western coast***, the ocean began to gain on the continent about the close of the Paleozoic, and the shore of the Pacific was presently shifted eastward to the vicinity of the 117th meridian in the latitude of Nevada.

In keeping with these changes in geography, Triassic strata are known in three regions: (1) The Atlantic slope east of the Appalachians; (2) the western interior; and (3) the Pacific coast. The strata in these three regions are in many ways unlike.

### *The Eastern Triassic*

**Distribution.** The Triassic system of the east occurs in spots from Nova Scotia to South Carolina, as shown in Fig. 412. Its several areas are mostly elongate in a northeast-southwest direction. The beds of these several areas have been grouped under the name *Newark* (Newark, N. J.).

Fig. 412. Map showing the known distribution of the Triassic system in North America (black areas), with conjectures as to its presence where buried (lined areas), and its absence where it was once present (dotted areas).

**Kinds of rock.** The rocks of this series[1] include all the common varieties of fragmental rocks, some of which are developed in unusual phases. Sandstones and shales predominate, but conglomerates and breccias are present, and, locally, limestone and coal.

Conglomerate lies at the base of the system in many places, and is made up chiefly of material from the underlying crystalline schist. Conglomerates also are the border phase of beds which grade laterally into sandstone, and even into shale. The chief constituent of the conglomerate is quartz, the most resistant part of the underlying terranes; but locally, quartzite, crystalline schist and limestone are severally its principal constituents.

Sandstone and shale make up the great body of the Newark series, and both possess distinctive characteristics. The prevalent color is red, though there are shales which are black, and sandstones which are gray. Some of the sandstone is arkose, that is, contains feldspar, and both sandstone and shale contain much mica. Both these constituents abound in the metamorphic rocks from which the Newark sediments were chiefly derived. Except locally, the series is poor in fossils.

**Conditions of origin.** The character of the Newark formations and their fossils, mainly land plants, footprints of reptiles, and fresh- or brackish-water fishes, indicate that they are of continental rather than marine origin, but do not tell the precise manner in

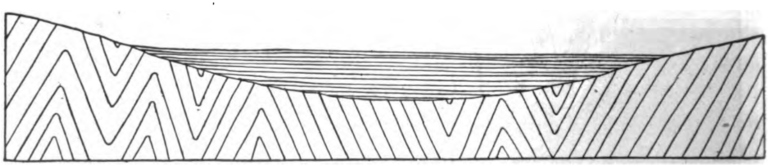


Fig. 413. Diagram showing the development of a trough, now partly filled by sediment, by warping.

which they were laid down. The depressions in which these beds were deposited may have been due to warping or to faulting, or partly to the one and partly to the other (Figs. 413 and 414). However formed, they became the sites of lakes, bays, estuaries, dry basins, or aggrading rivers.

The considerable thickness of the sediments, taken in connection

[1] The Connecticut valley and New York-Virginia areas are best known, and the descriptions of the formations here given apply especially to them.

with their decisive evidences of shallow-water or subaërial origin, such as ripple-marks, sun-cracks, tracks of land animals, etc., indicate either that the sediments were deposited in an inclined position, or that subsidence accompanied the deposition. For the

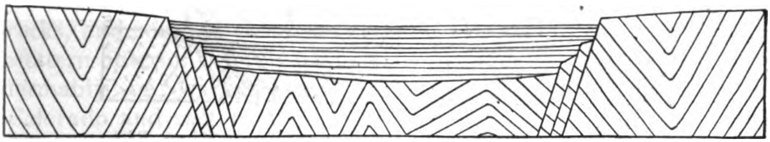


**Fig. 414. Diagram showing the development of a trough by faulting.**

adequate supply of sediment, it would seem that the lands bordering the areas of deposition were raised, relatively, as the troughs were filled.

**Former extent.** It is possible, and perhaps probable, that the areas of the Newark series from Virginia to South Carolina were once connected with one another, and with the Pennsylvania-New York area, though such connection has not been demonstrated. It has even been suggested that the Newark of the New York-Virginia areas was once connected with that of the Connecticut valley, and this with that of Acadia, the separation being effected by erosion; but this suggestion does not seem well founded.[1]

**Igneous rocks.** Igneous rocks are associated with the sedimentary beds in dikes, and in sheets interbedded with the shales and sandstones. Some of the sheets were extruded and subsequently covered by sediment; others were intruded (*sills*) between the layers of sedimentary rocks. Certain isolated bodies of igneous rock may represent volcanic plugs. The sheets of igneous rock (usually called trap, though largely basalt) vary in thickness from a few feet to several hundred.

**Structure and thickness.** The structure of the Newark series is generally monoclinal. In the Connecticut Valley the dip is about 20° (10° to 25°) to the eastward. In the New York-Virginia area [2] it is 10°–15° to the northwest. The strata are otherwise somewhat deformed, though never closely folded. The series is faulted extensively. On account of the faulting, the thickness of the series

[1] For summary of the Trias of Connecticut, see Davis, 18th Ann. Rept., U. S. Geol. Surv., Pt. II.

[2] For summary of the Newark of New York and New Jersey, see Kümmel, Rept. of the State Geologist of New Jersey, 1896, and Jour. Geol., Vol. VII.

is not easily determined. In the Richmond area of Virginia, it is estimated at something more than 3,000 feet; in New England, at 7,000 to 10,000 feet; and in New Jersey even more.

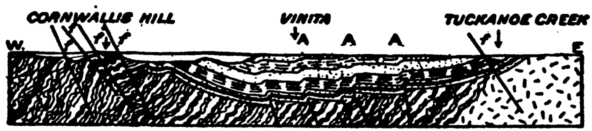



Fig. 415. Structure of the Newark series on the James River, Richmond area, Va. *AA*, minor flexures; *ff*, faults. Structure of the deeper parts hypothetical. The heavy black band represents coal. (Shaler and Woodworth, U. S. Geol. Surv.)

**Correlation.** The stratigraphic relations of the Newark series in the United States would not determine its age. It lies unconformably on rock which is mainly pre-Cambrian, and is overlain unconformably by Comanchean (Lower Cretaceous) beds. About the Bay of Fundy, however, the rocks are unconformable on the early Permian. The physical relations of the Newark series therefore show that it is post-early-Permian, and pre-Comanchean. In referring the series to the Triassic, the chief reliance is on the fossils, and on the same basis it is believed to represent only the later part of the period.

## *The Western Triassic*

**The western interior.**[1] The interior area of sedimentation, chiefly between the 100th and 113th meridians, had its southern limit, so far as now known, near the southern boundary of the United States, while at the north it extended into Canada. This area is believed to have been cut off from the Gulf by land in eastern Texas. Into this interior area of sedimentation, detritus was borne from the surrounding lands. The conditions of sedimentation were much as in the Permian period. The structure of some of the sandstone is such as to suggest an eolian origin.

The deposits of the period are largely concealed by later beds, but they are exposed at various points where the strata have been warped, and the overlying beds removed by erosion. The most easterly outcrops are in Texas, Oklahoma, and South Dakota, and

[1] There is some doubt about the age of some of the beds formerly referred to this system. The tendency of later study has been to refer more and more of them to the Permian.

red beds which are thought to be Triassic outcrop interruptedly along the eastern base of the Rocky Mountains from British America to New Mexico. These beds are thin, and contain more or less gypsum and salt. Here and there they contain fossil leaves.

Farther west, red beds have representation among the surface rocks, and some of them are perhaps Triassic; but in much of the western interior, undifferentiated Triassic and Permian rest conformably on Carboniferous (Pennsylvanian). In southwestern Colorado and eastern Utah, the Trias is unconformable on older, deformed, unfossiliferous red beds (presumably Permian), and on strata of Pennsylvanian age.[1]

In the eastern part of the western area, the Triassic system is thin, in places no more than 100 feet. To the west it thickens, reaching 2,000 to 2,500 feet in the Uinta Mountains, beyond which it again becomes thinner.

**The Pacific slope.** The Triassic system has here its greatest development in America. In the latitude of Nevada, the Pacific

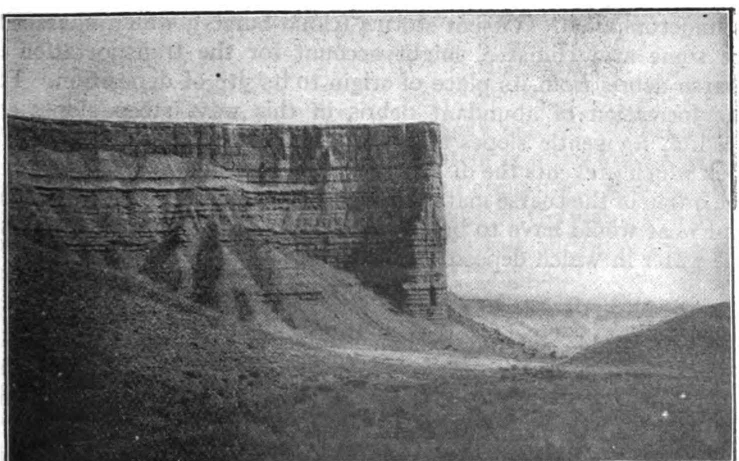


Fig. 416. Chugwater (Triassic) Red Beds near Shell, Wyo. (U. S. Geol. Surv.)

seems to have extended eastward over the site of the Sierras to longitude 117° (approximately). Farther north the shore line has not been located definitely. It probably was irregular, and, in

[1] Cross and Howe; Bull. G. S. A., Vol. xvi, p. 447.

general, several degrees farther east than now, well up into British Columbia. Between the latitudes of 55° and 60°, the sea is believed to have crossed the present Cordilleran belt.

The published measurements assign the system the great thickness of 17,000 feet (maximum) in the West Humboldt range of Nevada, where it rests on pre-Cambrian terranes. To have supplied such a volume of sediment, the land to the east must have been high, or repeatedly renewed, unless the great thickness is due to oblique deposition.

### *Climatic Conditions*

The wide distribution of gypsum and salt in the system, in more than one continent, is evidence of wide-spread aridity. The prevalent redness of the system, in other continents as well as our own, is also commonly regarded as an indication of aridity. Perhaps the peculiarities of the Newark conglomerate may find their explanation in such a climate, which favors great changes of temperature, and so the disrupting of rock, if it is not covered by soil. Under such circumstances, much coarse debris originates, largely of rock which is undecomposed. Violent storms (cloud-bursts), which characterize some arid climates, might account for the transportation of coarse debris from its place of origin to its site of deposition. For the formation of abundant debris in this way, steep slopes are needful, for gentle slopes and flats soon get a covering of mantle rock which prevents the disruption of the rock beneath. If this was the origin of the coarse materials of the conglomerate, their rounding and wear would have to be attributed to the waves or currents of the water in which deposition took place.

### *Close of the Trias*

Considerable geographic changes marked the close of the Triassic period in *eastern North America*, bringing the areas which had been the sites of deposition to higher levels, faulting the rocks, and affecting them by igneous intrusions. In the *western part* of the United States, the separation of the Triassic period from the Jurassic was not pronounced, and the sedimentary history of much of this part of the continent seems to have run an uninterrupted course from the beginning of the Permian to the later part of the Jurassic. The case may have been somewhat different north of the United States, for in British Columbia and in the adjacent islands, Triassic and older formations were upturned, deeply eroded, and again sub-

merged before the beginning of the Cretaceous. The great igneous formations associated with the Trias of the northwest appear to have been made during the Triassic period, rather than at its close.

### *Foreign Triassic*

**Europe.** In Europe, the Trias is exposed in many widely separated areas, the largest being in northwestern Russia; but the system is better known in the western part of the continent. In England, it is unconformable on the Permian, but on the continent, generally conformable. It has a marine and a non-marine phase. The non-marine (or *Triassic*) phase prevails throughout the northern part of the continent, while the marine (or *Alpine*) phase is found farther south. The former resembles the Permian of Europe, and the Permian and Triassic of the United States.

In general, the Upper Trias is more widespread than the Lower, especially in the southern part of the continent, and is marine over a wider area. The principal subdivisions recognized in Britain and Germany are the following:—

| *Britain* | *Germany* |
|---|---|
| Rhaetic | Keuper |
| Upper Trias | Muschelkalk |
| Lower Trias | Bunter |

In *Germany*, the middle member is largely marine, and the others chiefly non-marine. In *England* the system is often known as the New Red Sandstone, though formerly the Permian was also included under this term. It differs from the Trias of Germany chiefly in the absence of the marine member. Both salt and gypsum occur in workable quantities in some parts of England. The Triassic beds of most of *Russia* are similar to those of western Europe. In *southern Sweden*, the system contains coal.

The non-marine formations of red color, so characteristic of the Triassic system both in North America and Europe, afford another striking intercontinental analogy, and doubtless point to a common cause, or to similar widespread conditions.

The *Alpine* or marine phase of the Triassic has its best development in the eastern and southern Alps, and is made up of thick beds of limestone and dolomite, alternating with thinner beds of clastic rock. The limestone and dolomite are much more resistant than the associated shales, and, as a result, erosion has developed a distinctive topography (known as "the dolomites") at several points in

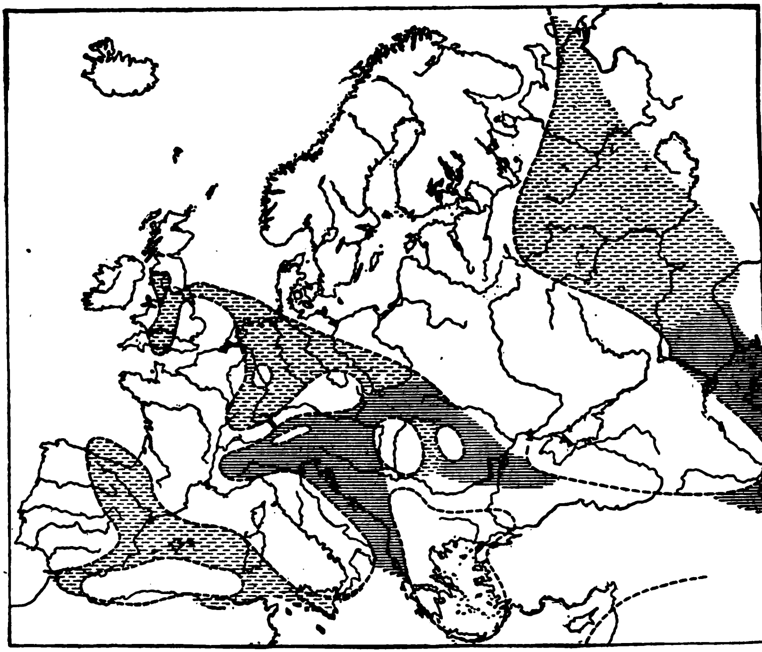


Fig. 417. Sketch-map of Europe showing areas of sedimentation in the early part of the Triassic period. The broken lines represent areas of non-marine deposits; the full lines, areas of marine deposits. (After De Lapparent.)

the southern Alps — a topography so striking that the localities where it is seen have become the objective point of travel, both for geologists, and for lovers of wild and picturesque scenery. In these regions the dolomite (limestone) stands up in bare, bold-faced walls, peaks, and towers, surrounded and separated by valleys and passes clothed with abundant vegetation. The decay of the projecting limestone leaves little soil behind, and the little formed is promptly carried away by wind and rain. The Trias of the western Alps is largely non-marine, and in some parts of Switzerland the Upper Trias contains coal and igneous rocks. The Trias of the Italian Alps is the source of the Carrara marble.

**Other continents.** The marine phase of the system, similar to that of southern Europe, continues eastward to southern *Asia.* It is found also in the high latitudes of Asia, including numerous

islands north of the mainland. The Trias here is generally conformable on the Permian and beneath the Jurassic.

In *South America* no marine deposits of Triassic age are known east of the Andes, but coal-bearing Trias occurs in Argentina and Chile, and marine beds at various points in the Andes. Thus it is clear that the site of parts of this great system of mountains was beneath the sea in the Triassic period.

The Triassic system is represented also in *South Africa*, *Australia*, *New Zealand*, and *New Caledonia*.

## LIFE

The remarkable physical conditions that impoverished the land life of the Permian period held sway during the early part of the Triassic, and the two periods were much alike in their general biological aspects, as in their physical conditions; but toward the close of this period there was a pronounced change. The land became lower and the sea encroached upon it, bringing about appropriate changes in life. Nearly all that is known of life in North America belongs to the later portion of the period.

**Plants.** Plant life was probably meager, for broad saline basins and arid tracts are inhospitable to it. At any rate, its record is scanty. The Triassic was distinctly an age of gymnosperms. Ferns and fern-like plants were still important but their dominance was past. The great lycopods, too, were almost gone, though sigillarias were among their lingering representatives. Calamites had given place to true equiseta, which were represented by gigantic forms. Among gymnosperms, cordaites had declined, and ginkgos (*Ginkgoales*) diverged from them at about this time. Conifers of the types that came in during the Permian, and kindred new ones, were prominent. The cycadean group (p. 685) occupied the place of central interest. The *Bennettitales* (p. 685), formerly called cycads, abounded, and from them the true cycads sprang. The Triassic floras of Europe and America, so far as known, were much alike. Both had a scrawny pauperitic aspect that reflected the hostile conditions in which they lived. In the far east and in the southern hemisphere, the genus *Glossopteris* and its allies constituted a marked feature of a flora whose general aspect was much like that of the preceding Permian flora in the same regions.

In the closing stages of the period an ampler flora seems to record some amelioration of the inhospitable conditions. The larger part

of the known American fossils belong to this stage. The Richmond coal-beds of the Newark series, probably the product of marsh vegetation, contain great numbers of equiseta and ferns, but almost no conifers and few cycadeans.

**Land animals.** The physical conditions of the Permian and Triassic periods were so similar that adaptation to the conditions of the first would seem to have been a fitting preparation for life in the second. Yet, in spite of this fact, there was a great break in the succession of land life, so far as the known record shows. What became of the Permian vertebrate faunas of North America is unknown, for between the horizons yielding Permian fossils of land animals, and those yielding Upper Triassic fossils of land animals, there are great thicknesses of red sandstone barren of fossils of all sorts, so far as now known, and the later fauna does not appear to have descended from the Permian. In Africa there appears to have been a much less serious break between the land life of the two periods. In other continents few Early and Middle Triassic fossils of land life have been found, but the life of the Upper Trias is better known. During the period many types were initiated, while only a few reached their maximum development.

There is abundant proof of the mingling of European and American land faunas late in the period, for at this time there were, in North America, representatives of groups that had lived in Europe since the early Permian, but which had never before appeared in our continent, so far as now known.

Though still numerous the *amphibians* had lost the foremost place they held in the Permian. Before the close of the period they entered upon a rapid decline from which they never recovered. Ancestors of the whole tribe of terrestrial vertebrates, they soon became its most insignificant representatives.

*Reptiles* evolved rapidly. The branch with the mammalian strain (p. 478, Fig. 418) seems to have been left far behind by the more distinctively reptilian branch, which developed greatly later in the period when the dryness was ameliorated and vegetation began again to flourish. Before the close of the period, every important group of the class was represented. Crocodilians, flying saurians, and the scaled reptiles (lizards, snakes, etc.) came in near the close of the period, as some of the older types were disappearing.

A foremost feature of the life was the advent and rapid evolution of the *dinosaurs* (terrible saurians). At first they were of

generalized types, but later became more specialized, and widely divergent. While some were small and delicate in structure, others were gigantic and ungainly. Carnivorous forms only (*Theropoda*)

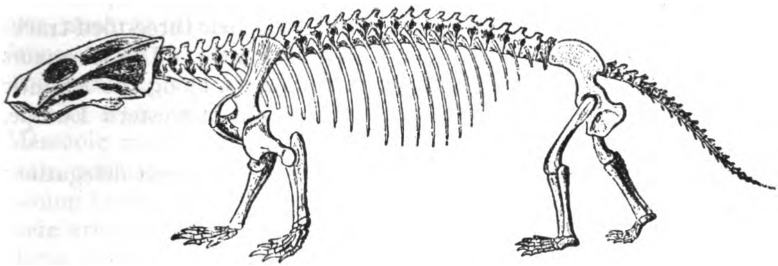


Fig. 418. *Oudenodon trigoniceps;* an anomodont (or dicynodont) from the Karroo of South Africa, similar to forms of the Trias in Wyoming. (After Broom.)

are known in the Trias, and most of them were not especially large. Their general form is indicated by the partially restored skeleton shown in Fig. 419. The strength of the hind parts, the relative

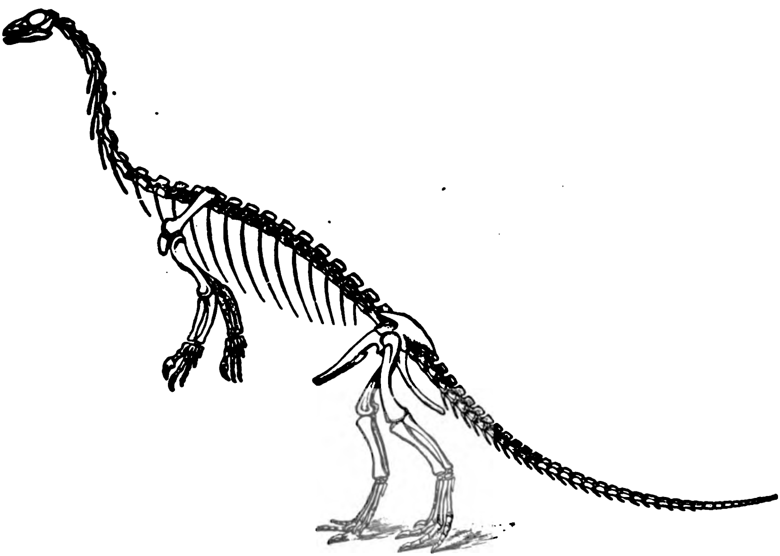


Fig. 419. A Triassic dinosaur of the Connecticut Valley, *Anchisaurus colurus;* restored by Marsh; 1/30 natural size.

weakness of the fore limbs, and the kangaroo-like attitude, are the most obvious features. The bones of the upright-walking forms were hollow, and some other structural features resemble those of birds. The reduction of the toes of the hind feet to four, with one of them much shorter than the others, caused their three-toed tracks to be mistaken for those of birds, until recently. The dinosaurs had wide range, living in the Rocky Mountains, along the Atlantic coast from Carolina to Prince Edward Island, in western Europe, India, and South Africa.

Before the close of the period the reptilian tribe sent delegations

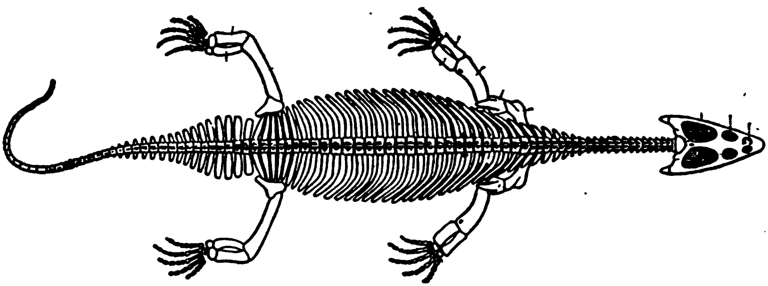


Fig. 420. A Triassic sauropterygian, *Lariosaurus balsami*, restored; about 1/11 natural size; from the Muschelkalk, Lombardy, Italy. (After Woodward.)

to sea (Fig. 420), but marine forms were more plentiful in the next period.

*Advent of mammals.* Of especial interest is the appearance of early form of mammals. They were small, and so primitive in type that it is not altogether certain that they were mammals; but they are commonly regarded as such, with kinship to the marsupials. Their appearance while reptiles were yet dominant suggests that mammals diverged from the primitive stock much earlier. In view of the mammalian dominance of later times, it is noteworthy that they developed but slowly and feebly during the Mesozoic era.

**Marine life.** Except along the Pacific coast, there is, in North America, little record of the marine life of the Triassic period; but in Europe the record is better. While the sea withdrew from the northwestern part of Europe during the Permian period, it lingered about the Mediterranean, in Russia, Turkestan, and northwestern India, and probably on the continental platform in or near Siberia. The Mediterranean, the Himalayan, and the Siberian regions are the best known tracts into which the shallow-water marine life of

the late Paleozoic retreated and gave rise to the early provincial faunas of the Mesozoic.

In each of these three areas an important remnant of Paleozoic sea life seems to have undergone a radical and perhaps rapid evolution, such as might be anticipated from the crowding of the great faunas of earlier times into limited areas. From these areas the new faunas spread when the sea again extended itself upon the land.

The most complete record of the transition from Paleozoic to Mesozoic marine life is found in India. Beds containing fossils characteristic of the Permian are overlain conformably by beds containing forms characteristic of the Mesozoic. In the Permian beds there are forms foreshadowing the Mesozoic types, and in the beds above there are Permian types that lived on and mingled with Mesozoic forms. The transition fauna of the Mediterranean region appears to have been less rich. Concerning the early stages of the Siberian fauna, little is known; but its peculiarities, as revealed in a later stage of the early Trias, leave little doubt of its independence of origin.

It is quite certain that there was at least one other area where important faunal reorganization took place, for a notable fauna appeared suddenly in the Middle Triassic, which does not seem to have originated in any of these three districts.

*Geographic suggestions of the faunas.* The alliance of the Indian forms with those of North America is so close as to indicate that before the close of the early Trias, migratory connections had been established between India and western America.

Somewhat later in the early Trias there appeared in the Siberian region (Olenek River) a fauna having some of the same genera as the Indian. Closely related species are found in Idaho. If there was connection between the Indian and Siberian regions, it would be possible for Indian species to reach America from Siberia either by way of the Arctic coast, or by the Pacific sea-shelf, and slight changes, involving submergence or emergence in the region of Bering Strait might change the combination of the faunas.

The Indian and Siberian provinces seem to have been distinct from the Mediterranean province throughout the earlier Triassic; but in California a few fossils have been found which are characteristic of the earlier Triassic of southern Europe.

The early Triassic faunas of central Europe were very diverse, a part being developed apparently in fresh water, a part in isolated

seas, and a part perhaps in gulfs and bays. The marine life was scanty, and its origin and relations uncertain; but it seems to have been largely independent of the Mediterranean basin.

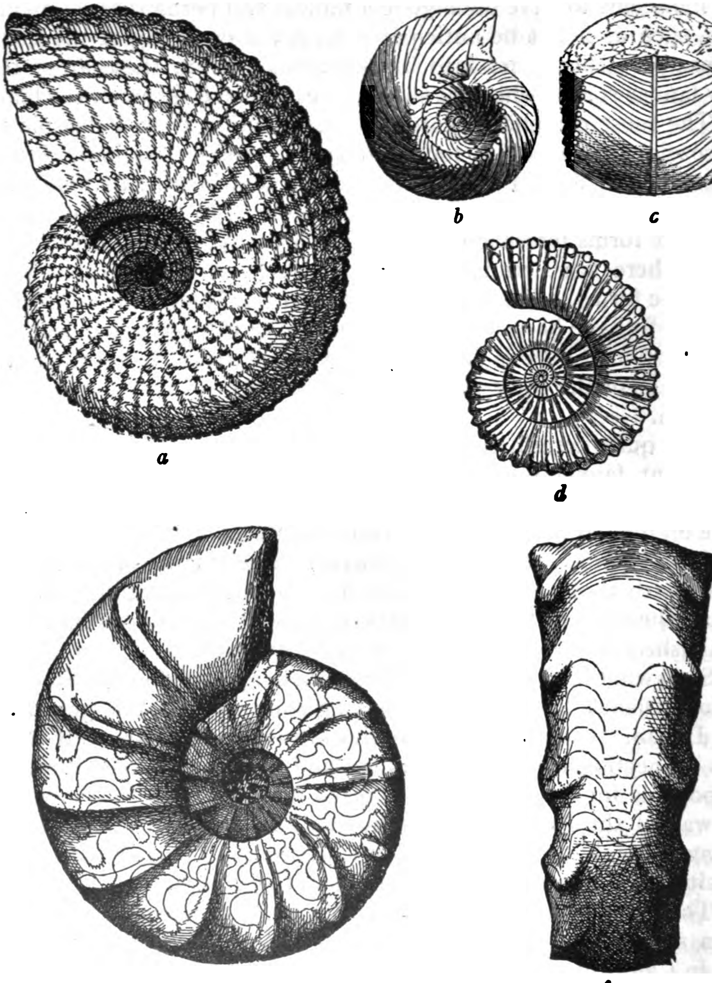



Fig. 421. A Group of Triassic Cephalopods. *a*, *Trachyceras austriacum* Mojs.; *b-c*, *Tropites subbullatus* Hauer; *d*, *Choristoceras marshi* Hauer; *e-f*, *Ceratites nodosus* de Haan, lateral and ventral views of the shell.

By the middle of the Triassic period the faunas had begun to intermingle, and to lose their provincial characteristics. The Mediterranean fauna gained access to the Indian basin and to our western coast, and counter-migrations were of course made possible. At about the same time, the Siberian fauna had access to western United States.

During the later stages of the period a rich marine fauna flourished in California. Many of its species were identical with those of the Mediterranean and Himalayan regions, or closely allied to them. It is therefore inferred that these provinces were in free communication, so far as marine life was concerned, with the west American coast.

*Prominent types.* The most conspicuous feature of the Triassic faunas was the re-ascendancy of the *cephalopods* in the form of the *ammonites* (Fig. 421), which had a marvelous development during the period, reaching a thousand species. Their evolution was the more notable because the structural changes were conspicuous, and showed plainly the advance of each stage over the preceding. While early types still persisted, closely coiled, intricately-sutured forms predominated. The first representatives of the cuttlefish type appeared at this time. The deployment of the cephalopods was therefore greater than ever before, though they did not reach their culmination till the next period. Old forms, orthoceratites and goniatites, made their last appearance in this period. The remarkable commingling of old and new types makes this one of the most instructive assemblages in the history of the cephalopods.

A similar commingling of transitional forms was presented by the *gastropods*, and the progress of the *bivalves* was scarcely less real, though they do not show the transition from ancient to modern so conspicuously. Their numbers were large, and most of their genera modern, some being identical with those now living. With the modern types there were about half as many that still bore a Paleozoic aspect.

The dominant *brachiopod* types of the late Paleozoic were distinguished by extended hinge-lines, while the narrower beaked or rostrate forms were in a respectable minority. In the Triassic period the latter became predominant, and have remained so ever since. (Compare Figs. 422 and 367.)

Among *echinoderms*, leadership passes from the crinoids to the sea-urchins. Starfishes and brittle-stars were present, but not abundant.

*Corals* were rare in most places, but abundant in favored localities. Some of them resembled Paleozoic forms in being simple and cup-shaped, but compound species took on the modern (*hexacoralla*) form, and the compound Paleozoic (*tetracoralla*) type

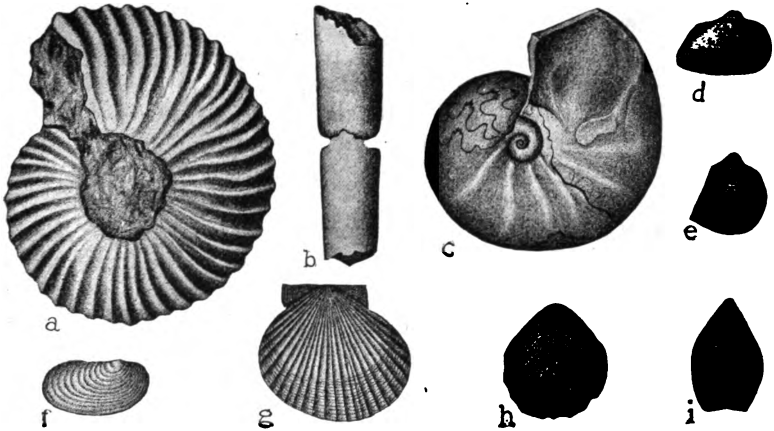



Fig. 422. Group of Marine Triassic Fossils. *a*, *b*, and *c*, cephalopods: *a*, *Ceratites whitneyi* Gabb; *b*, *Orthoceras blakei* Gabb; *c*, *Meekoceras*. *d-g*, pelecypods: *d*, *Corbula blakei* Gabb; *e*, *Myopharia alta* Gabb; *f*, *Myacites humboldtensis* Gabb; *g*, *Pecten humboldtensis* Gabb; *h* and *i*, brachiopods: *h*, *Rhynchonella æquiplicata* Gabb; *i*, *Terebratula deformis* Gabb.

disappeared. These later compound corals do not seem to have descended from the compound Paleozoic forms, but from some simple type.

Though the general aspect of the Triassic marine faunas was revolutionary, it was yet transitional, and not a new fauna substituted for an old one. Paleozoic types lived side by side with later forms, though in most cases represented by new genera. This overlapping and commingling of old and new indicates clearly the gradation of the earlier into the later. The transition was extraordinary in the apparent rapidity of its progress, and in the extent to which it affected all classes. The fact that most of the new types lived at the beginning of the Triassic indicates that the transition was chiefly in the Permian. The fundamental cause was, with little doubt, the readjustment of the earth's surface to internal stresses, and the physiographic and climatic changes consequent upon this readjustment.

Marine reptiles seem to have thriven on the western coast of our country, especially in the middle and later Trias. The numerous ichthyosaurs found in the later Triassic beds of this region suggest that it may have been a center of dispersion of these reptiles. With the ichthyosaurs were other reptiles (*thalattosaurs*) unknown elsewhere.

# CHAPTER XXIII

## THE JURASSIC PERIOD

### FORMATIONS AND PHYSICAL HISTORY

**Eastern North America.** Jurassic formations have not been identified in the eastern half of the continent, where erosion seems to have been the leading geologic process during the period. Its effectiveness may be judged by the fact that both the uplifted and deformed Triassic system and the Appalachian mountain region farther west were essentially base-leveled before the next period was far advanced.

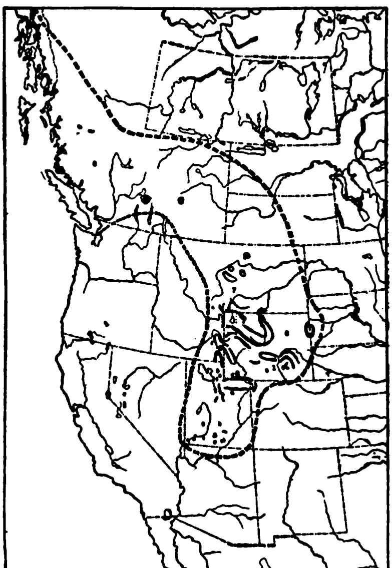


Fig. 423. Map showing the general relations of land and water in the western part of North America during the later part of the Jurassic period. The black areas represent known areas of Upper Jurassic. The dotted line is the conjectured outline of the bay. (After W. N. Logan.)

**Western interior.** Deposition was in progress, probably, in some parts of the western interior, though early Jurassic beds of this region have been clearly differentiated from the Trias in but few places. There is perhaps room for doubt whether the lower and middle parts of the system have much representation in this region.

Late in the period, an arm of the sea covered a large tract in the western interior, covering much of Wyoming, Montana, Utah, and Colorado, and parts of several other states (Figs. 423 and 424). This is shown by the presence in these states of sedimentary beds containing marine fossils of late Jurassic age. The avenue

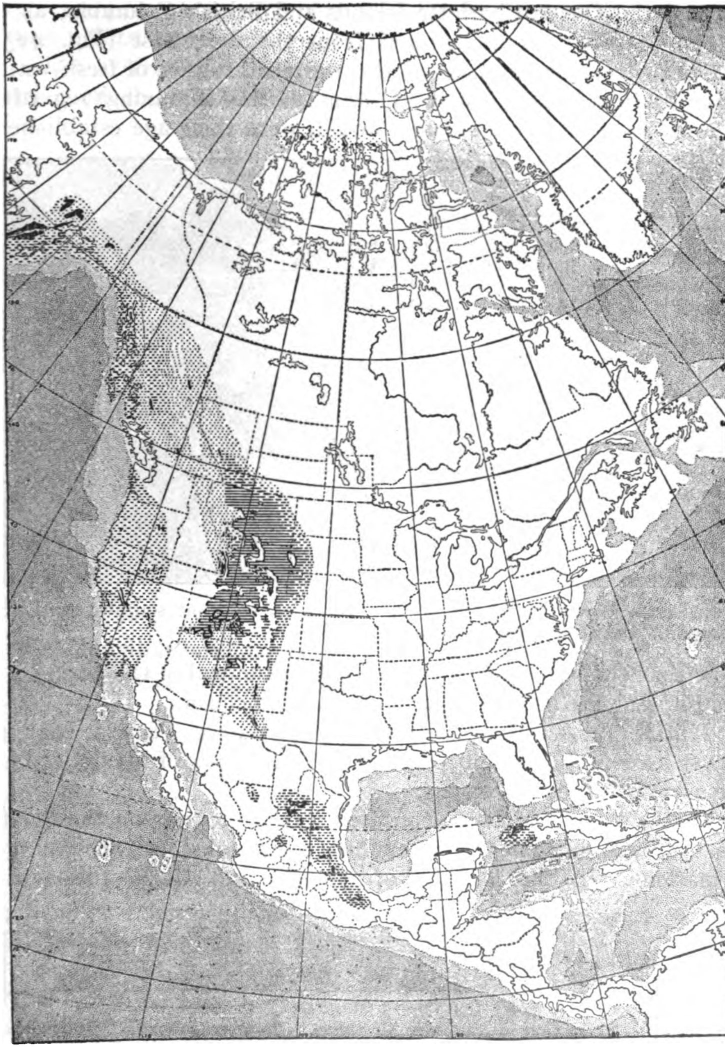


Fig. 424. Map showing the areas where the Jurassic system appears at the surface in North America. The conventions are the same as on preceding maps.

through which the sea entered has not been determined, but the fossils of the interior are so unlike those of California, and so like

those of the Queen Charlotte Islands and British Columbia, as to suggest that the waters entered from the northwest (Fig. 423). The presence in some parts of the western interior, of fresh-water beds (*Morrison* beds of Colorado, Montana, and Wyoming) regarded by some as of late Jurassic age, would, were their age established,

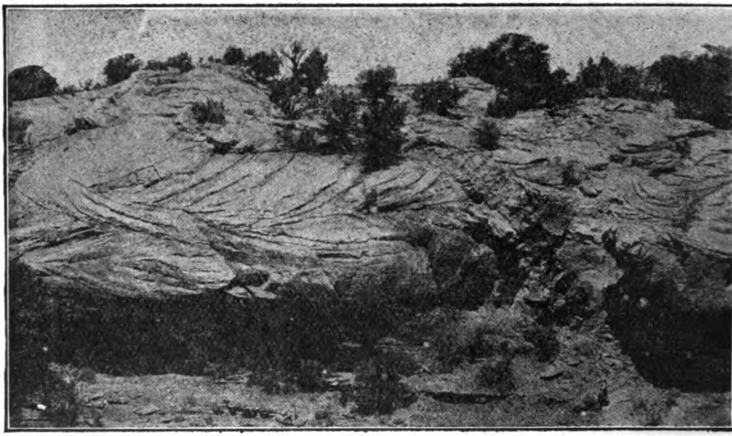


Fig. 425. Lower part of the LaPlata (Jurassic) sandstone, southwest of La Sal Mountains, Utah. (Cross, U. S. Geol. Surv.)

show that the sea-water withdrew before the end of the period. If not Jurassic, the beds in question are Comanchean.

Marine Jurassic limestone occurs in western Texas. Its connections are probably southward with the Jurassic of Mexico, where the system is well developed.

**Pacific coast.** Marine deposition was in progress on the Pacific coast, though much of the system here is concealed beneath younger formations. In the latitude of Nevada and Utah, the earlier

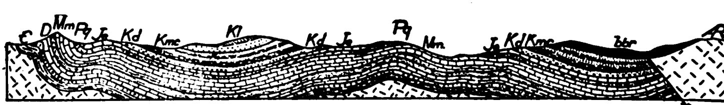



Fig. 426. A section in southern Montana. *Æ*=Archean; €, Cambrian; *D*, Devonian; *Mm*, Mississippian; *Pq*, Pennsylvanian; *Je*, Jurassic; *Kd*, *Kmc*, and *Kl*, Cretaceous; *bbr*, igneous rock. (Peale, U. S. Geol. Surv.)

formations of the period extended east to longitude 117°. The Lower Jurassic beds generally rest on the Trias conformably where

both are present, but the younger beds overlap the older system at some points, and fall short of it at others.

The system contains the common sorts of sedimentary rocks, and some fragmental igneous rock. Jurassic formations also are

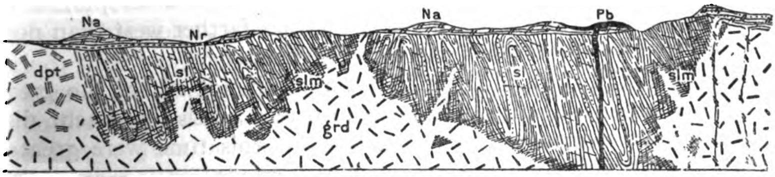



Fig. 427. Section in the Sierras of California. The Jurassic (or Jura-Trias) has been metamorphosed, and is associated with igneous rock. *grd* and *dpt*, igneous rock, probably of Jurassic or Cretaceous age; *sl* and *slm*, Jura-Trias (?) schist; *Na*, *Nr*, and *Pb*, igneous rock, late Tertiary and Pleistocene. (Lindgren, U. S. Geol. Surv.)

known at somewhat widely separated points in Alaska.[1] On the shores of Cook Inlet, 10,000 feet of Middle and Upper Jurassic are reported.

**Thickness.** The total thickness of the system in California does not exceed 2,000 feet (in part tuff). Farther east, in western Nevada, nearer the land whence sediment was derived, it attains a thickness twice or thrice as great. In the western interior, it is thin.

**Surface distribution and position of beds.** The Jurassic beds do not now appear at the surface over large areas, being much concealed by younger beds. In some areas they retain their original position, while in others they have been tilted, or even folded or metamorphosed (Fig. 427). This is especially the case in the Sierra Mountains and in some ranges near the western coast.

## *Close of the Period*

**Orogenic movements.** At the close of the Jurassic period, there were considerable disturbances in the western part of North America. Great thicknesses of Triassic and Jurassic strata began to be folded into the Sierras, and the Cascade and Klamath mountains farther north perhaps began their growth. It is not to be understood that these mountains attained great height at this time, or that they have not had later periods of growth. It is probable that the Coast Range of California began its history at the close of this period, for deformed Jurassic beds (*Golden Gate* series) underlie

[1] See Alaskan Reports, U. S. Geol. Surv.

the Lower Cretaceous unconformably in the axis of the range; but the movements which gave the Coast Range its present form (modified by erosion), took place much later. Various other ranges of the west are thought to have begun their history as mountains at about the same time. After this closing-Jurassic period of orogenic movement, the coast was somewhat farther west than now in northern California and southern Oregon.

Toward the close of the period, much, if not all, of the great Upper Jurassic gulf of the northwestern part of the continent disappeared. All in all, the deformations at this time were greater than those which mark the close of most periods.

### *Foreign Jurassic*

**Europe.** Jurassic strata are exposed in many and widely separated parts of Europe, though for the most part in small areas only. It has been thought that the Jurassic of England is probably continuous with that of France beneath the English Channel, and thence, by way of southeastern France, with those parts of the system which appear about the Mediterranean, and by way of Belgium, the Netherlands, and the German lowlands, with those parts which appear in Poland and Russia. The lower part of the system (*Lias*) is less extensive than the Middle, and the Middle less widespread than the Upper. Progressive submergence was, indeed, one of the features of the period.

Among the more distinctive features of the system in Europe are the following: (1) A considerable content of coal in some places, notably Hungary. (2) The abundance of oölitic limestone, both in England and on the continent. (3) The presence of lithographic stone (Solenhofen limestone of southern Germany). This stone is so fine and so even-grained, and at the same time so workable and so strong, that it has come into use the world over for lithographic purposes. The stone is also remarkable for the perfection of its fossils, including such delicate parts as the gauzy wings of insects. (4) The considerable development of non-marine beds in the lower part of the system, and again at its very top.

The close of the period in Europe was marked by a somewhat widespread emergence of land. In central Europe, the emergence began before the close of the Jurassic, for the latest beds (Purbeck) of the system in England are unconformable on beds lower in the system. Similar changes are known to have occurred in late

Jurassic time in some other regions. On the other hand, the Upper Jurassic and the Lower Cretaceous beds are in places so closely associated as to show that no change of continental dimensions brought the Jurassic period to a close.

**Other continents.** The Upper Jurassic is widespread in *Arctic* lands. This points to a great Arctic sea in the later part of the period, with two considerable dependencies to the south — the one in Russia, the other in western America. The Lower Jura is wanting in these latitudes, so far as known, and the Middle Jura is limited. The Lower Jura occurs in southwestern *Asia* and *Japan.* The Middle Jura, largely clastic and of terrestrial origin, is widespread in Northern Asia, and marine Middle Jura is known in northern India. The Upper Jura is much more extended, especially in the north. The system is known in New Zealand, Borneo, Australia, and South America (Peru, the Bolivian Andes, Chile, and Argentina).

**Coal.** Coal is somewhat widely distributed, occurring in Hungary, the Caucasian region, Persia, Turkestan, southern Siberia, China, Japan, and Farther India, in many of the islands southeast of Asia, in Australia and New Zealand. Most of the coal is in the lower part of the system (Lias). Outside of North America, it is probable that no other system except the Pennsylvanian contains so much coal.

### *Climate*

The testimony of fossils gathered in various parts of the world is to the effect that the climate of the Jurassic period was genial. In Europe, corals lived 3,000 miles north of their present limit, and saurians and ammonites flourished within the Arctic circle. Nevertheless, climatic zones probably were defined. The detailed study of the faunas has led to the belief that one climatic zone is recorded in the Jurassic beds of the Arctic belt, a second in the deposits of central Europe, and a third in the southern province of Europe and lands farther south.

## LIFE

The Jurassic was a period of sea extension, and the marine life again assumes a place of leading importance in the fossil record. At the same time the land life, though suffering somewhat by the smaller area available for it, was favored by genial climate.

**Marine life.** The faunal progress of the period is less well revealed in North America than in Europe and Asia. The great

features were (1) the continued dominance of ammonites among the invertebrates, (2) the rise of the belemnites, (3) the abundance and modernization of pelecypods, (4) the rejuvenation of corals and crinoids, (5) the marked development of sea-urchins, (6) the introduction of crabs and modern types of crustaceans, (7) the prevalence of foraminifera, radiolaria, and sponges, (8) the

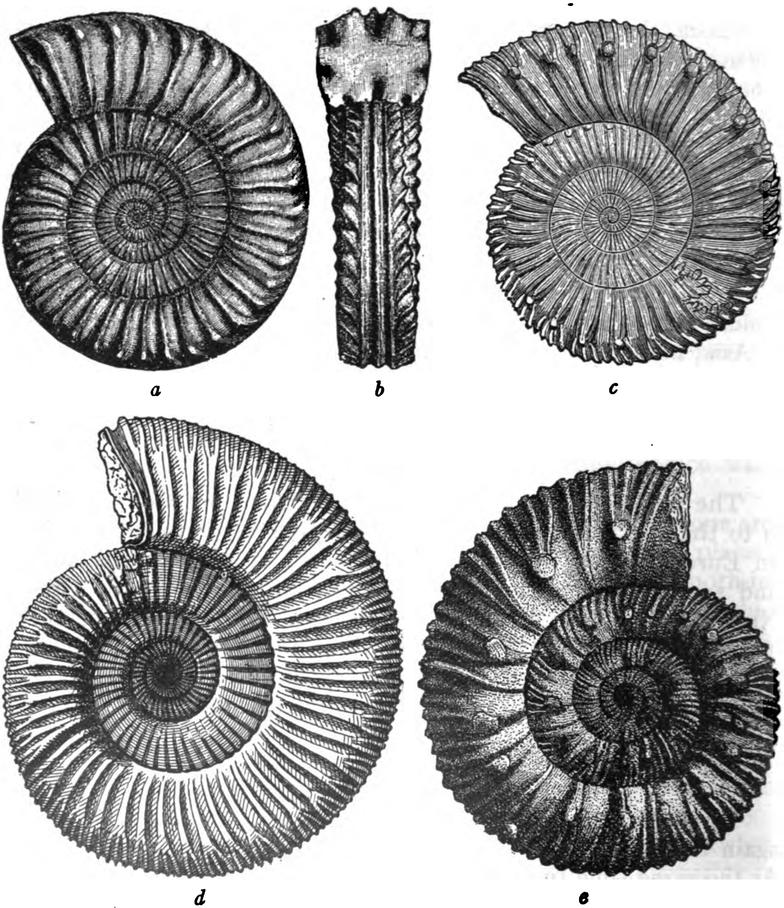



Fig. 428. GROUP OF JURASSIC AMMONITES. *a-b*, ***Coroniceras bisulcatum*** (Brug.), a lateral and ventral view of one of the ***Arietidæ***; *c*, ***Deroceras subarmatum*** (Young); *d*, *Perisphinctes tiziani* (Oppel); *e*, ***Reineckia brancoi*** Steinm.

change in the aspect of the fishes, and (9) the great sea-serpents, descended from land-reptiles.

(1) The *ammonites* were represented by many beautiful forms (Fig. 428). They deployed along ascending lines in most cases, but erratic and degenerate tendencies showed themselves. Despite these adverse foreshadowings, the ammonities were still in the heyday of their luxuriance and beauty.

(2) Another division of cephalopods, the *belemnites*, had appeared in the Trias, and rose to prominence rapidly. They are represented in the fossil state chiefly by their internal shell or "pen" (Fig. 429).

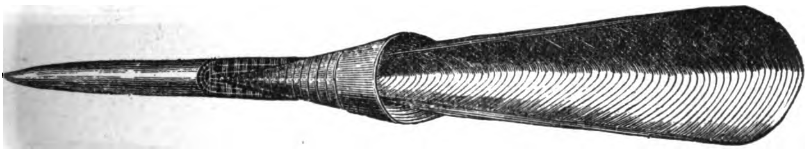


Fig. 429. The internal shell of a *belemnite*, restored; the lower, solid, conical portion (at the left in the Fig.), the part most commonly preserved, is the rostrum or guard; the middle portion is the *phragmocone*, which is a diminutive chambered shell with septa, siphuncle, and protoconch as in the older tetrabranch order; the upper part is the *prostracum*, which corresponds to the "pen" of living cuttle-fish.

In the course of the period the belemnites came almost to rival the ammonites, and were almost as characteristic of the successive stages of deposition. The first known cuttle-fishes also appeared at this time.

(3) *Pelecypods* flourished during the period (Fig. 430), and, took on a markedly modern aspect, the oyster family taking the lead. Gastropods were abundant in some places, but singularly absent in others. Existing genera were represented.

(4) Suggestive of shallow clear seas was the reappearance of *corals* and *crinoids* in abundance in the later part of the period. The modern type of corals (*Hexacoralla*) was in the ascendant and formed reefs, especially in European seas. Crinoids also rose again to prominence, though their diversity was not great. Most of them lived in shallow water, as most of the Paleozoic types had; but there is evidence that deep-water species had appeared, leading toward the prevalent habit of the present.

(5) The slow evolution of the *sea-urchins* in the Paleozoic era was succeeded in the late Trias by the beginning of a rapid evolution, which reached its climax in the early Tertiary.

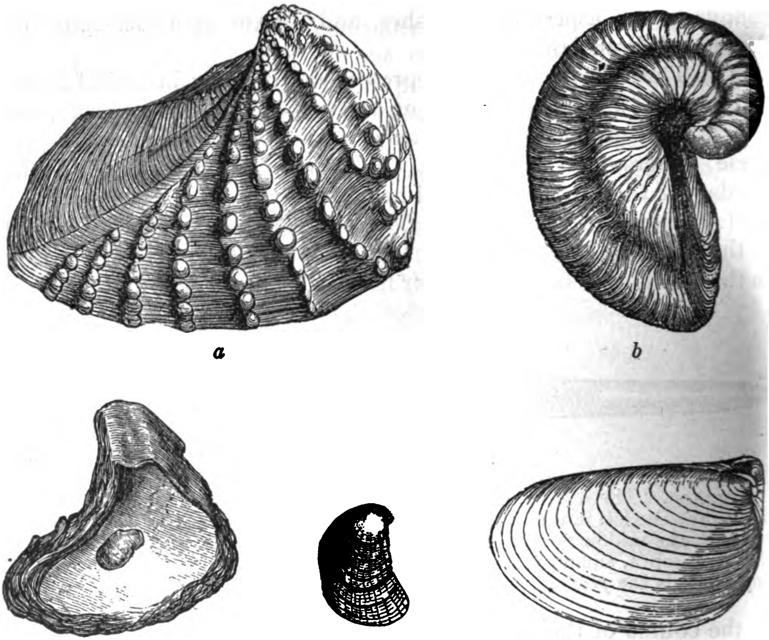



Fig. 430. GROUP OF JURASSIC PELECYPODS. *a*, *Trigonia navis* Lam.; *b*, *Gryphæa arcuata* Lam.; *c*, *Ostrea deltoidea* Sby.; *d*, *Exogyra* (*Ostrea*) *virgula* D'Orb.; *e*, *Aucella mosquensis* Keys.

(6) The trilobites of the sea, and the eurypterids of land waters, had been succeeded by *decapods* which rose to a moderate and prolonged ascendancy. The prawns and lobsters (*Macrura*, long-tailed decapods) were the earlier division, and the most numerous in this period; but the first known crabs (*Brachyura*, short-tailed decapods) appeared before the period was past. The macrurans seem to have frequented embayments and protected locations near the land, or perhaps within it, for terrestrial, fresh-water, and marine species are preserved in the same sediments. Probably macrurans had representatives in terrestrial waters then, as now.

(7) *Sponges* and *foraminifera* abounded and are well preserved.

(8) The marked change in the aspect of the *fishes* which set in during the Trias was carried farther in this period. Some of the older types declined; but the selachians (sharks) remained abundant,

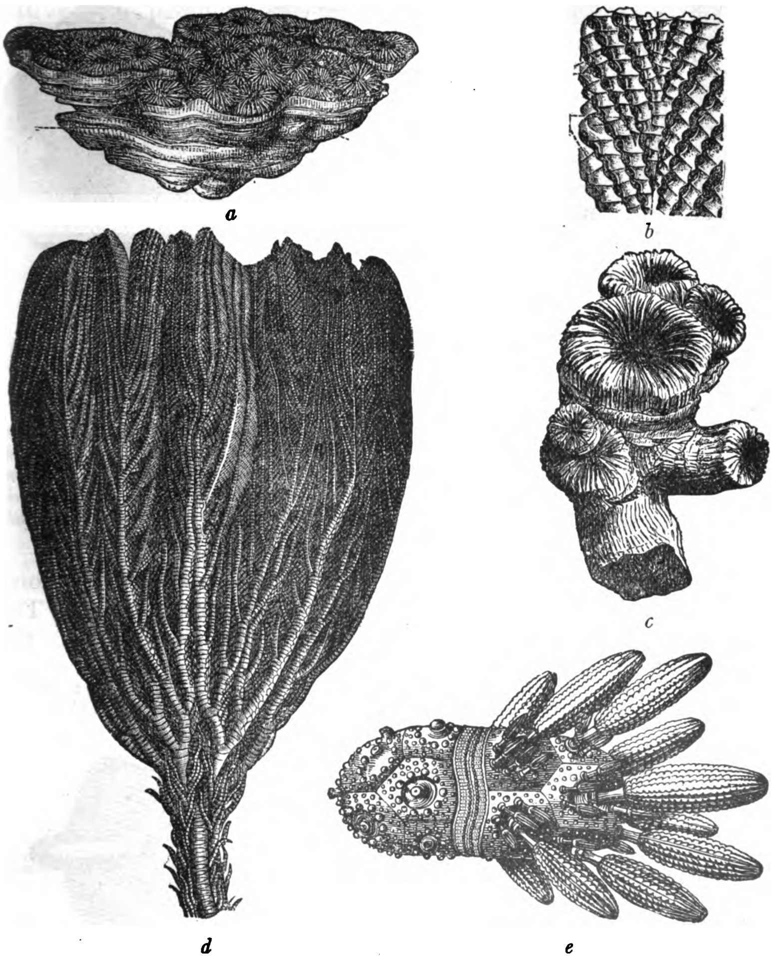



Fig. 431. Jurassic Cœlenterata and Echinodermata. *a* and *b*, *Thamnastræa prolifera* Becker, a complete corallum, and the lateral surface of a costal septum, enlarged; *c*, *Thecosmilia trichotoma* (Goldf.); *d*, *Pentacrinus briareus* Mill; *e*, *Cidaris coronata* Goldf.

skates and rays began their modern career; the existing family (*Chimæridæ*) of sea-cats or spook-fishes made its appearance, so far as fossils show (Fig. 434); the forebears of the living garpikes

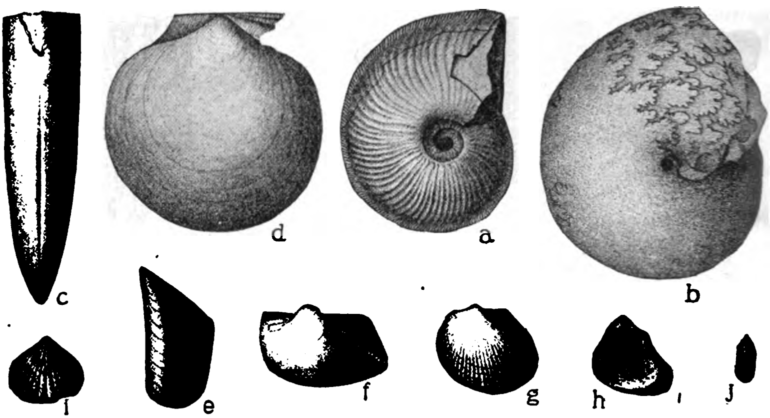



Fig. 432. JURASSIC FOSSILS. *a-c*, Cephalopods: *a*, *Cardioceras cordiformis* M. and H.; *b*, *Neumayria henryi* M. and H.; *c*, *Belemnites densus* M. and H. *d-h*, pelecypods: *d*, *Camptonectes bellistriatus* Meek; *e*, *Mytilus whitei* Whitf.; *f*, *Grammatodon inornatus* M. and H.; *g*, *Pseudomonotis curta* (Hall); *h*, *Ostrea strigilecula* White. *i* and *j*, brachiopods: *i*, *Rhynchonella gnathophora* Meek; *j*, *Lingula brevirostra* M. and H.

and sturgeons were numerous, and the initial forms of the bony fishes (*teleosts*), the dominant type, made their appearance. The class was distinctly more modern than at the close of the

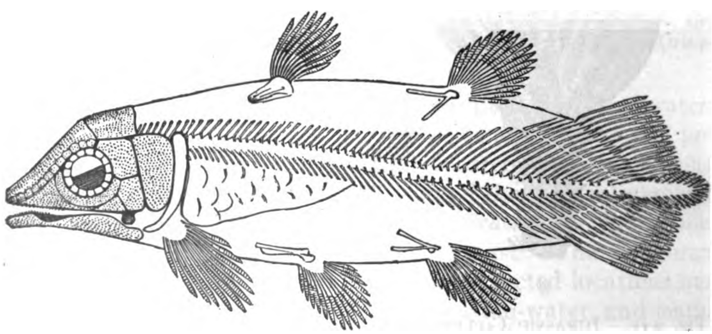


Fig. 433. A Jurassic cœlacanth, *Undina gulo*, a crossopterygian, about 1/7 natural size; the outline of the air-bladder is shown just back of the gills and under the axis. (Restored by A. Smith Woodward.)

Paleozoic. Though the *fishes* doubtless suffered from the reptiles which went down to sea in the Trias, it appears that they continued in notable abundance and variety. It will be seen later that they

outlived the invading race, and resumed, in large measure, their former dominance.

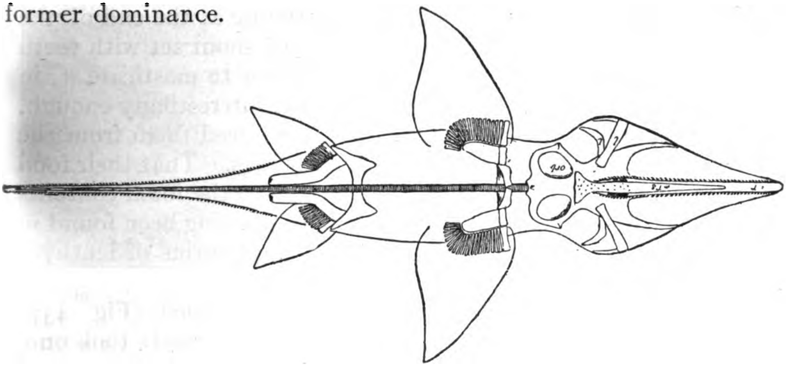


Fig. 434. A Jurassic spookfish or chimæroid, *Squaloraja polyspondyla*, ¼ natural size; from the Lower Lias, Dorsetshire. (Restored by A. Smith Woodward.)

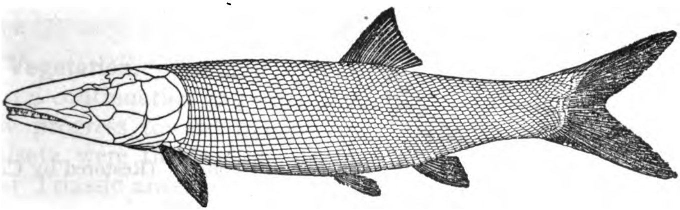


Fig. 435. A Jurassic forerunner of the modern *Amia*, *Eugnathus athostomus*, about 1/7 natural size, from the Lower Lias, Dorsetshire. (A. Smith Woodward.)

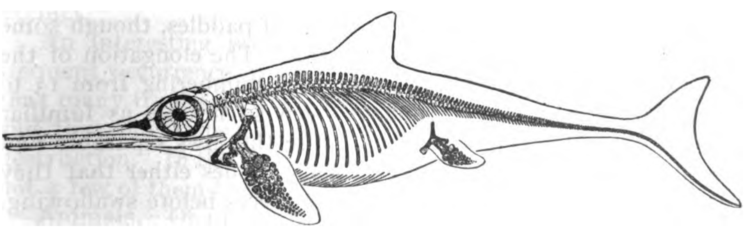


Fig. 436. Outline and skeleton of *Ichthyosaurus quadriscissus*. (After Jaekel.)

(9) Some of the reptiles which had taken to the sea in the preceding period had become extinct, while others made their first appearance in this period. The *ichthyosaurs* (fish-like saurians) reached their highest development in this period, and seem to have swum every sea. Their adaptation to aquatic life is shown in the complete transformation of their limbs into paddles (Fig. 436), in

the reduction of the outline of the body to fish-like lines and proportions, in the sharp down-bending of the vertebræ at the end of the tail for the support of a caudal fin, in the long snout set with teeth adapted to seize and hold slipping prey, but not to masticate it, in the protection of the eye by bony plates, and, interestingly enough, in the development of a viviparous habit that freed them from the necessity of returning to land to deposit their eggs. That their food consisted in part of invertebrates is evident from the fossil contents of the stomachs, the remains of 200 belemnites having been found in a single one. There were small as well as large forms of ichthyosaurs, some exceeding 30 feet in length.

Descended from a different stock, the *plesiosaurs* (Fig. 437) adapted themselves to sea life in another way. The body took on a

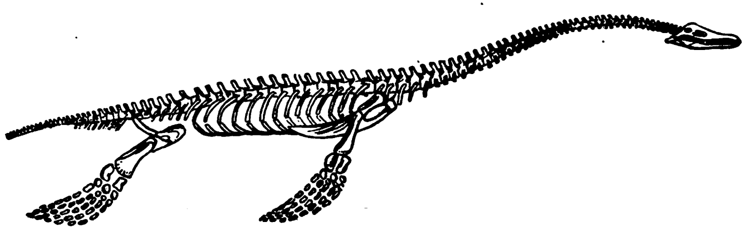


Fig. 437. Skeleton of *Plesiosaurus dolichodeirus* Conyb. (Restored by Conybeare.)

form like that of a turtle, while the neck was elongate, giving rise to the epigrammatic description "the body of a turtle strung on a snake." Swimming was chiefly by means of paddles, though some forms had a fin-like adaptation of the tail. The elongation of the neck was variable, the vertebræ of the neck numbering from 13 to 76. The neck appears not to have been so flexible as familiar illustrations have represented it, nor were the jaws separable and extensible as in the case of snakes. This implies either that they lived on small prey, or tore their food to pieces before swallowing. They were doubtless formidable foes of the smaller sea animals, but probably not of the larger. Like ichthyosaurs, they were without scales. They ranged from 8 to 40 or more feet in length.

Marine *crocodilians* made their appearance late in the period. They had undergone a remarkable adaptation to the sea (Fig. 438). They were fish-like in appearance, their skins were bare, and their tails terminated in a fin like that of the ichthyosaurs. The fore limbs were short and paddle-like. The hind limbs were modified

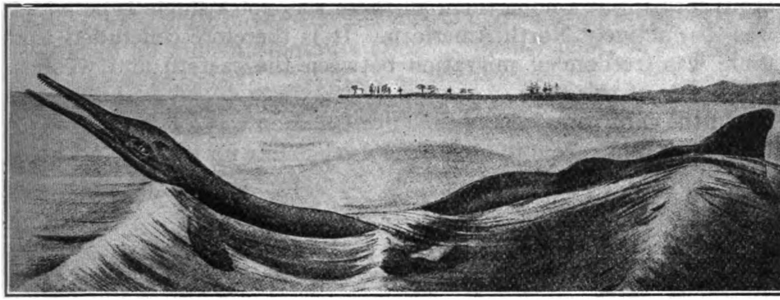


Fig. 438. Restoration of a Jurassic crocodilian, *Geosaurus suevicus*. (Fraas.)

but slightly from the land type, perhaps due to the recurring necessity of visiting the shores for depositing and hatching eggs. Marine turtles, so characteristic of the Cretaceous, had not yet appeared.

### *Land Life*

**Vegetation.** The land vegetation of the Jurassic was little more than a continuation and expansion of that of the late Triassic, with slow progress toward living types. Cycads, conifers, ferns, and equiseta were the leading plants, slightly more modernized than their Triassic ancestors, but not changed radically.[1] The conifers were represented by yews, cypresses, arborvitas, and pines, all of which had a somewhat modern aspect, though all the species are extinct.

An interesting feature of the European record is the rather frequent occurrence of land plants in marine beds, which implies that many trunks, twigs, leaves, and fruits were floated out to sea, and that the landward edges of the marine deposits have escaped destruction. In the same beds are the remains of many land insects, not a few of them being wood-eating beetles.

**Animals.** Of the early Jurassic land faunas of North America little is known; but in the Morrison beds (perhaps Comanchean, p. 504) there is a fauna composed chiefly of dinosaurs. Some of these reptiles were large, and some small, and the group as a whole had great diversity in many directions. There were not only carnivorous types, which had appeared in the Trias, but numerous herbiv-

[1] Jurassic plants of the United States, with descriptions and illustrations by Lester F. Ward; 20th Ann. Rept., U. S. Geol. Surv., pp. 334–430.

orous forms; but among them all there was not a single type which was distinctively North American. It is therefore concluded that there was freedom of migration between the eastern and western continents at this time.

Of the carnivores, one of the most common was a type (Fig. 439) whose fore limbs seem to have been used chiefly for seizing and hold-

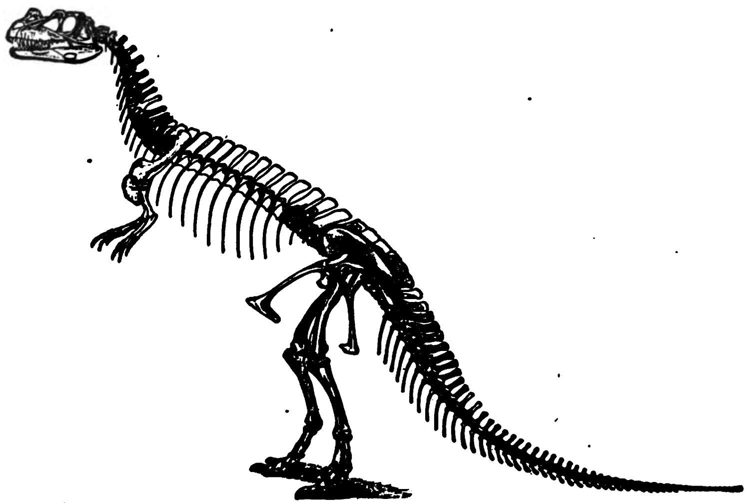


Fig. 439. A carnivorous dinosaur, *Ceratosaurus nasicornis*, about 1/40 natural size; i.e., length about 17 feet; from the Como beds, Colorado. (Restoration of skeleton by Marsh.)

ing prey, rarely for walking. The animal's pose was facilitated by hollow bones. The head was relatively large, an unusual character for a race among which small heads and brains were the fashion. Besides the large ones, there were small leaping forms not larger than a rabbit.

The herbivorous dinosaurs, known first in this system, developed so rapidly that they soon outranked the carnivorous forms in both size and diversity. Most of them were massive, with sub-equal limbs and the quadrupedal habit. Some of them (Fig. 440) attained a length of 60 feet (possibly more), taking rank among the largest of known land animals. These enormous creatures were characterized by weakness rather than strength, for they were unwieldy, their heads and brains small. "The task of providing food for so

large a body must have been a severe tax on so small a head." The largest of all known dinosaurs (*Brachiosaurus*) had a femur nearly

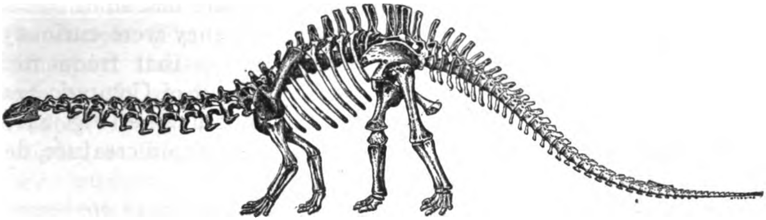


Fig. 440. An herbivorous dinosaur, *Brontosaurus* (*Apatosaurus*): Restoration of skeleton by Riggs, nearly 60 feet long; from Wyoming.

7 feet long. There were other genera of similar nature, and of bulk inferior only to these monsters.

The typical ornithopod (bird-footed) dinosaurs were bipedal in habit, like the carnivores. On the hind limbs there were usually only three functional toes, so that they left a bird-like track; the fore limbs, however, had five digits. One of the largest of this group

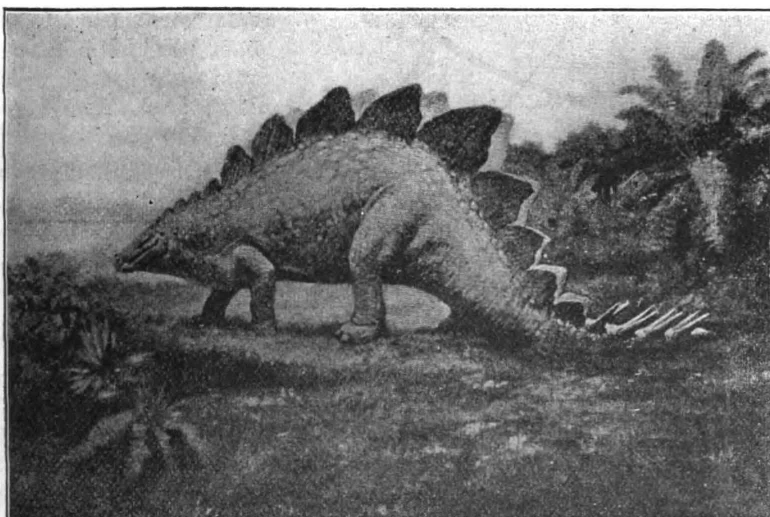


Fig. 441. *Stegosaurus*, an armored dinosaur of the Jurassic. Interpreted by Charles R. Knight. (Lucas' *Animals of the Past*. By permission of the publishers, Messrs. McClure, Phillips and Company.)

measured about 30 feet in length, and 18 in height in the walking posture.

The *stegosaurs* were quadrupedal in habit, and had solid bones. Though not so large as some of the preceding, they were curiously armored, and formed a very remarkable group that frequented England and Western America. The *Stegosaurus* of Colorado and Wyoming (Morrison beds) was one of the most unique (Fig. 441). Its diminutive head and brain imply a sluggish, stupid creature, depending for protection on its bulk and armor.

A unique feature of the period was the development of *pterosaurs*, or flying reptiles. Appearing at the close of the Trias in a few yet imperfectly known forms, they were at the opening of this period,

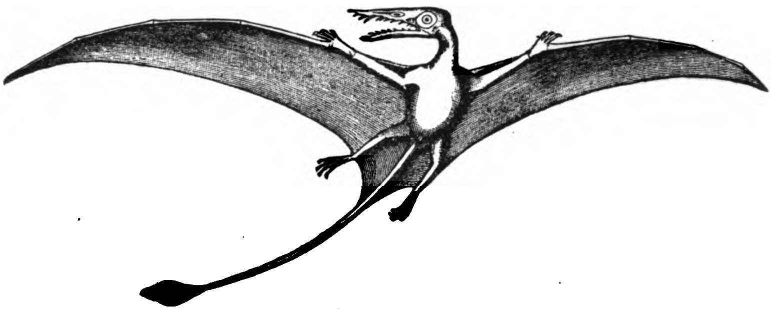


Fig. 442. *Rhamphorhynchus phyllurus*, a flying saurian. (Restored by Marsh.)

fully developed flying animals, and later formed a diversified group which included long-tailed (Fig. 442) and short-tailed forms (Fig. 443). With little doubt they sprang from some agile, hollow-boned saurian, more or less akin to the slender, leaping dinosaurs. Between the ponderous forms (Figs. 440, 441) and the pterosaurs (Fig. 442), the Jurassic saurians present strange contrasts.

Jurassic pterosaurs were small, but their successors attained a wing-spread of nearly a score of feet. They were curiously composite in structure and adaptation. Their bones were hollow, their fore limbs modified for flight, their heads bird-like, and their jaws set with teeth, though toothless forms appeared later. They were provided with membranes stretched, bat-like, from the fore limbs to the body and hind limbs, which served as organs of flight (Fig. 442). The fifth, or as some paleontologists believe, the fourth front digit was greatly extended, and supported the wing-membrane. The sternum was greatly developed, implying true powers of flight,

a conclusion supported by the occurrence of their remains in marine sediments free from other land fossils. Some of them had singular elongate rod-like tails, with a rudder-like expansion at the end. *Pterodactyls* (Fig. 443) had short tails, and were mostly small and slender. Fully differentiated as first found, they underwent no radical change of structure during their career, and the steps of their remarkable evolution are for the most part unknown. Flying reptiles are extremely rare among the Jurassic fossils of North America.

*Turtles*, which had lived elsewhere since the Middle Trias, made their first appearance in North America in the Morrison beds, and the *crocodilians* became differentiated into several branches. Primitive lizards were doubtless abundant, but because of their terrestrial habits and small size, they have little representation among the fossils, and none have been found in our continent.

Fig. 443. Skeleton of pterodactyl, *Pterodactylus spectabilis*, from the lithographic stone at Eichstadt, Bavaria; about ¾ natural size. (After H. v. Meyer.)

A less bizarre, but really greater evolution, was the differentiation of true *birds*. The remote ancestors of the pterosaurs and the birds may have been closely allied, but there is no evidence that birds descended from pterosaurs. The two are examples of analogous and parallel evolution, not of relationship.

The oldest known bird, *Archæopteryx macrura* (Fig. 444), shows clear traces of a reptilian ancestry. From this ancestry it retained a long, vertebrated tail, reptile-like claws, teeth set in sockets, biconcave vertebræ, and separate pelvic bones. On the other hand, its head and brain were bird-like, its anterior limbs adapted to flying in bird-

(not pterosaurian) fashion, its posterior limbs modified for bird-like walking, and most distinctive of all, it was clothed with feathers. The presence of feathers, while yet the body retained so many reptilian features, is remarkable. But for their preservation, it is uncertain whether the creature would have been classed as a bird or reptile. The known specimen was somewhat smaller than a crow.

The marvelous deployment of aquatic and terrestrial reptiles and of birds makes the scanty record of the ***mammals*** all the more singular. Only a few jaw bones of the size of those of mice and rats have been found. These low types are referred, without complete certainty, to marsupials. They appear to have been insectivorous.

Fig. 444. The earliest known bird, *Archæopteryx macrura*. The long vertebrated tail, the clawed digits of the fore limbs, and the toothed jaws are ancestral features to be specially noted. (H. von Meyer.)

The insects of the Jurassic appear to have included members of nearly all fossilizable groups not dependent on flowering plants.

*Map work.* For suggestions as to map work see *Laboratory Exercises in Structural and Historical Geology*, Exercise X.

# CHAPTER XXIV

## THE COMANCHEAN (LOWER CRETACEOUS) PERIOD

**Definition.** The history of the Cretaceous period, as formerly defined, was complex. At its beginning, the larger part of the North American continent was above the sea. During its progress, the sequence of events in our continent was somewhat as follows: (1) A somewhat widespread warping of the continental surface, resulting in extensive submergence in Mexico and Texas, and a lesser submergence along the Pacific coast. At about the same time the Atlantic and Gulf coasts and some parts of the western interior were sites of deposition, though not submerged. Prolonged sedimentation followed. (2) Geographic changes which inaugurated a long period of erosion that affected the recent deposits as well as older formations. (3) Encroachment of the sea submerging the Coastal Plain of the Atlantic and the Gulf of Mexico, and presently the Great Plains, probably to the Arctic Ocean. On the Pacific coast, too, the sea gained on the land. Few greater transgressions of land by sea are recorded in the long history of the North American continent. A long period of deposition was initiated by the submergence. It was succeeded by (4) a widespread withdrawal of the waters from the continent, leaving the land area nearly or quite as large as now.

The formations of the Cretaceous period have been divided, commonly, into two main series, a Lower and an Upper. To the former were referred the deposits of the earlier and lesser submergence, and to the latter, those of the later and more extensive submergence. The distinctness of the Lower and Upper Cretaceous is, however, so great that it is more in keeping with the spirit of modern classification to regard them as separate systems, and the corresponding divisions of time as periods. What was formerly called the Lower Cretaceous series is here called the Comanchean system. The propriety of this classification is the more striking, since it is applicable to other continents as well as to our own.

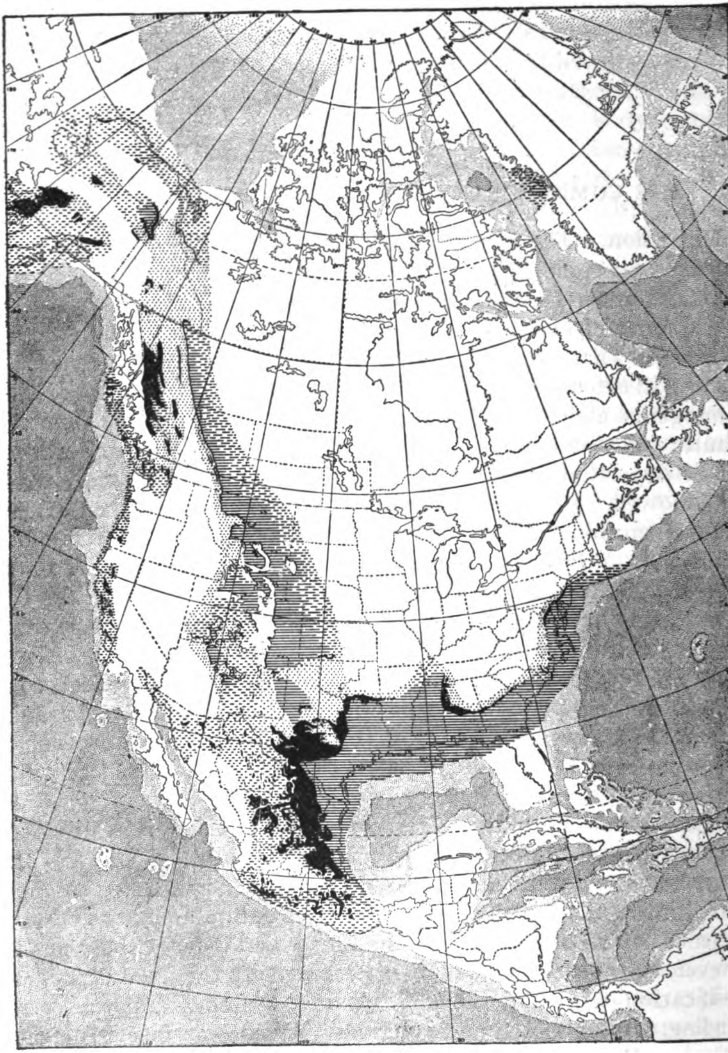


Fig. 445. Map showing the distribution of the Comanchean formations in North America. The conventions are the same as in preceding maps.

### FORMATIONS AND PHYSICAL HISTORY

**Atlantic and Gulf border regions.** That part of the Comanchean system along the Atlantic coast is called the *Potomac* series; the part along the eastern Gulf coast, where conditions of sedimentation appear to have been similar, is the *Tuscaloosa* series. Fig. 445 shows that the system outcrops near the inland margin of the Coastal Plain. It is the lowest of the Coastal Plain formations. Neither the Potomac nor the Tuscaloosa series is believed to represent the whole of the period, and the two are not strictly contemporaneous.

*Conditions of origin, and constitution.* By the beginning of the Comanchean period, both the Appalachian Mountains and the area to the east had been degraded well toward base-level, so that little warping of the surface appears to have been needed to convert portions of the coastal lands into sites of deposition, though more may have been necessary to provide lands high enough to furnish abundant sediments. The peneplanation of the eastern mountains during the Jurassic period was no doubt attended by deep decay of the underlying rocks, and the consequent accumulation of a heavy mantle of residuary earth. The warping which inaugurated the Comanchean period seems to have involved a rise of the Appalachian tract, and a consequent rejuvenation of the drainage from it, while the coastward tract was left relatively low and became a zone of lodgment for the sediments brought down by the quickened drainage from the west. Lakes, marshes, etc., probably were features of the lodgment area. The deposits consist of gravel (or conglomerate), sand (or sandstone), and clay, largely uncemented.

The gravel and sand came chiefly from formations to the west. Both are arkose (containing particles of crystalline rock, not decayed when deposited) locally, showing that erosion sometimes exceeded rock decay. This suggests high land to the west whence the sediments were derived, and is one of the reasons for the belief that it was tilted upward at this time. Beds of clay in the Potomac series have been utilized extensively, especially in New Jersey,[1] for the manufacture of clay wares. Some of it is notable for its bright and variegated colors, black, white, yellow, purple, and red being not uncommon. White is to be looked upon as the normal color; the others are the result of various impurities, the black being due to organic matter.

[1] Cook, Geol. Surv. of New Jersey, 1868, and Kümmel, 1904.

The clay, sand, and gravel are disposed irregularly, doubtless the result of the physical conditions where the sedimentation took place, conditions which might have existed along the lower courses of rivers or at their debouchures, where shore-waters had little effect upon them.

In addition to the clastic sediment, there is a little lignite, and some iron ore, and though both are widely distributed, neither is of much commercial value.

*Structure and thickness.* The Potomac and Tuscaloosa series are nearly horizontal, with a gentle dip seaward. The Potomac

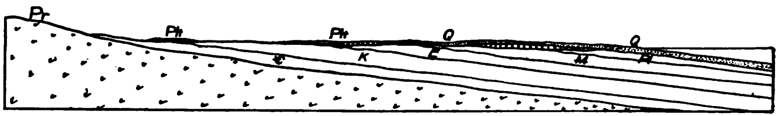



Fig. 446. Section showing relations of various members of the Coastal series. *C*, Comanchean; *K*, Cretaceous; *E*, Eocene; *M*, Miocene; *Pl*, Pliocene; *Q*, Quaternary.

series rests unconformably on Triassic and other formations (Fig. 446), and the Tuscaloosa on Paleozoic or older strata. Both series are overlain unconformably by the Upper Cretaceous. The Potomac formations reach a thickness of 700 feet in but few places. The thickness of the Tuscaloosa series is about twice as great.

**Western Gulf Region.** The system is more fully represented in Texas than farther east, but its stratigraphic relations are the same. The beds appear at the surface over an area distant from the coast, dip seaward at a low angle, and are concealed near the coast by younger formations. The lower part of the system (the *Trinity* series) is perhaps the time equivalent of the Potomac, while the uppermost series (the *Wichita*) is probably younger than any part of the system on the Atlantic coast. Some parts of the system, especially the middle (*Fredericksburg*) are marine, and some terrestrial. The marine part includes much limestone. The system here is much thicker than farther east, ranging from 1,000 feet to about 4,000.

From Texas, the Comanchean formations, or some of them, originally spread northward into Kansas, northwestward to Colorado, and westward to Arizona. Though they appear at the surface in small areas only, their extent may be considerable beneath younger formations.

The Comanchean of Mexico is mainly limestone, and, though but imperfectly known, has been estimated to have the extraordinary thickness of 10,000 to 20,000 feet. Its distribution is such as to show that a large part of that country was beneath the sea. It has been conjectured that the waters of the Atlantic and Pacific met over the site of some part of Mexico at this time, but this is uncertain. If the oceans were connected, it was probably across southern Mexico, or perhaps Central America. At any rate, there does not seem to have been free faunal intermigration between the Gulf coast and the coast of California.

**Northern interior.** The sea is not known to have extended north of Kansas during the period; but clastic beds of terrestrial origin, and perhaps of Comanchean age, are known at various points farther north. The beds in question, the *Morrison* (p. 504) beds, are best known along the Front Range through Colorado and Wyoming, and in the Black Hills, though they probably reach northward to Montana. If all the beds thought to be the equivalent of the Morrison are really so, the formation is widely distributed. These beds are regarded by some as Jurassic, and this may be their proper classification.

In Montana, Alberta, and Assiniboia, there are beds (the *Kootenay* and *Cascade* formations, etc.) similar in character to those just mentioned. They are mainly clastic, and contain some coal. Their fossils are mostly of plants of early Cretaceous types. In Montana, the Kootenay formation overlies the Morrison.

To the Morrison and Kootenay formations a lacustrine origin has usually been assigned, and there is perhaps no adequate ground for questioning this conclusion for some parts of the formations; but the character of some of the beds and the nature and distribution of their fossils suggest a fluviatile origin for parts, and perhaps for large parts, of the series.

**Pacific border.** The system (known as the *Shastan* group) has great development in California, where it attains its maximum known thickness. It is made up of the *Knoxville* series below and the *Horsetown* series above. The deposits are thickest in the Sacramento valley. Most of the thick system, including its basal beds, bears the marks of shallow-water origin. The Shastan group is represented in Oregon also.

Where the base of the system has been observed, it is unconformable on Jurassic rocks, or on metamorphic rocks of unknown

age. It is overlain unconformably in some places, and without apparent unconformity in others, by the (Upper) Cretaceous (*Chico* series).

Farther north, Lower Cretaceous beds (*Queen Charlotte* series) occur in the Queen Charlotte Islands,[1] where they have an estimated thickness of between 9,000 and 10,000 feet. In British Columbia, the coast line was east of the Coast ranges, and extended farther and farther east with increasing latitude, until the ocean swept clean across the site of the Cordillera in the early part of the period, and extended south along the area which is now the east base of the mountains.[2] The Kootenay formation is perhaps partly contemporaneous with these marine beds. The Comanchean system of British Columbia generally rests unconformably on the Triassic system, and contains some volcanic material and, locally, coal.

Farther north, the Lower Cretaceous has not always been separated from the Upper, but the former has extensive development in some parts of northern Alaska, where it contains coal. It occurs also on the west coast of Greenland, where the beds are thought to represent some such horizon as that of the Kootenay, or Potomac.

## *Close of the Period*

Considerable changes in the geography of North America brought the Comanchean period to a close. Along the Atlantic and Gulf borders considerable tracts were converted from areas of deposition into areas of erosion. The system was somewhat deformed and faulted in both Texas and Mexico. In the southern Coast Range of California there was folding of the Lower Cretaceous beds, accompanied by volcanic activity, while in other places the sea spread itself over areas which had been land. Still other areas in the west appear to have emerged at this time, and never to have been submerged since.

On the whole, the deformative movements at the close of the period were more extensive, so far as present knowledge goes, than those which occurred in the midst of any one of the Paleozoic periods as here defined. On stratigraphic grounds, therefore, the distinctness of the two systems is clear. The case is hardly less clear on the paleontological side.

[1] Dawson, Geo. M., Am. Jour. Sci., Vol. XXXVIII, 1889, pp. 120–127.

[2] Dawson, Science, March 15, 1901; Bull. Geol. Soc. Am., Vol. XII, p. 87.

### *Lower Cretaceous in Other Continents* [1]

**Europe.** The deposits in some of the lakes, marshes, estuaries, and other lodgment basins which resulted from the geographic changes at the close of the Jurassic period in Europe, record the transition from that period to the early Cretaceous. The interruption of marine sedimentation in Southern Europe was not so general, and over considerable areas the Lower Cretaceous succeeds the Jurassic conformably, both being marine.

During the early stages of the Lower Cretaceous, the areas of sedimentation were more or less isolated; but later, advances of the sea united many of them. The Lower Cretaceous formations include all sorts of clastic rocks, together with limestone, glauconitic beds, beds of coal (northwestern Germany), and iron ore. They embrace, indeed, about all varieties of sedimentary rock except chalk, the rock from which the name "Cretaceous" was derived. In southern Europe, much of the system is limestone.

**Other continents.** In other continents, the Lower and Upper Cretaceous have been less clearly differentiated; yet enough is known to show that the Lower and Upper Cretaceous systems are, in general, markedly different, both in origin and distribution. Marine Lower Cretaceous is well developed in the western part of the Andes Mountains. It is widespread also in the northern part of South America, but not elsewhere east of the Andes. It is generally absent about the borders of the South Atlantic. On the other hand, marine Lower Cretaceous beds occur in many places about the southern Pacific and Indian Oceans. Lower Cretaceous formations of marine origin are widespread also in Siberia and Japan. The system is believed to have slight development in the mountains of northwestern Africa, where it is really an extension of the Lower Cretaceous of southern Europe, and is unconformable beneath the Upper Cretaceous, and in South Africa.

Geographic changes of importance occurred in various parts of the earth at the close of the early Cretaceous period, as shown by (1) the unconformities between the Lower (Comanchean) and Upper Cretaceous systems, as at some points in Europe, north Africa, Australia, and South America, and (2) in the differences in their distribution.

[1] The term Comanchean is not applied to the Lower Cretaceous formations outside of North America.

### *Climate*

In the aggregate, the known fossils of the Lower Cretaceous of America are not such as to indicate great diversity of climate. Even in Greenland, the climate seems to have been as warm as that of warm temperate regions to-day.

The fresh-water fossils of those deposits of central Europe which represent the transition from the Jurassic to the Lower Cretaceous, indicate a climate far from tropical. It would seem to have been comparable to that of the temperate portions of America to-day. The fossils of lower latitudes denote a warmer climate. On the whole, European fossils seem to afford better evidence of the existence of climatic zones than those of America.

## LIFE

**Land vegetation.** Fossil plants constitute the chief record of the life of the early stages of the Comanchean in America. The earliest flora was akin to that of the Jurassic, the cycadeans (Fig. 447), conifers, ferns, and horsetails being the dominant forms. In most of Europe, this group held possession of the land throughout the period, though angiosperms appeared in Portugal before its close. Descendants of Jurassic types of plants also continued throughout the period in northwestern America.

*Introduction of angiosperms.* This period was marked by one of the most radical evolutions in the history of the plant kingdom. Angiosperms (p. 685), including both monocotyledons and dicotyledons, appeared early in the period, and developed so rapidly that by the beginning of the next they had overrun the continent. Their precise time and place of origin is not known, but present data point to the borders of the north Atlantic as the place of origin, and the late Jurassic or earliest Comanchean as the time.

About 400 species of Comanchean angiosperms are known from the Atlantic coast. They were in a minority in the lowest Potomac, but increase to an overwhelming majority in the upper beds. The earliest forms are not really primitive, and throw little light on the origin of the group. The majority resemble modern genera, and a few (as *Sassafras*, *Ficus*, *Myrica*, and *Aralia*) are referred to living genera. Before the end of the period, figs, magnolias, tulip trees, laurels, and other forms referred to modern genera, but not to modern species, had appeared. By this time the cycadeans had dropped

to an insignificant place, and the conifers and ferns, while not equally reduced, were subordinate to the angiosperms.

**Land animals.** The aspect of the vertebrate life was intermediate between that of the Jurassic and Upper Cretaceous, and, so

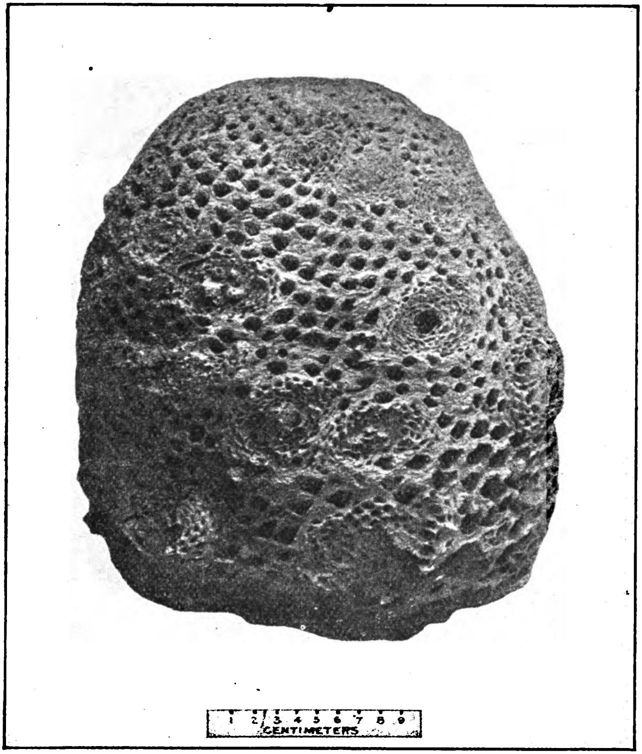



Fig. 447. A cycadean trunk from the Black Hills, Dakota, *Cycadeoidea dakotensis* Ward, Lower Cretaceous. (Ward.)

far as it is known, has been sketched already (p. 515). Little is known of other forms of terrestrial animal life, but it has been conjectured that the great development of flowering plants was connected with the existence of abundant insect life.

**Fresh-water fauna.** The molluscan fauna of the inland waters had assumed a pronouncedly modern aspect, as illustrated in Fig.

448. It probably had attained considerable importance through the extension of the fresh waters, but the record is by no means so ample as would be expected if the deposits were made mainly in lakes and river channels. This is an additional reason for the growing opinion that the terrestrial deposits were in considerable part the products of land-wash of the more transient type, due to overflows, storm-wash, sheet-wash, and other forms of more strictly subaërial aggradation.


Fig. 448. Fresh-water Fossils of the Comanchean (Lower Cretaceous) from Montana. *a* and *b*, Pelecypods: *a*, *Unio farri* Stanton; *b*, *Unio douglassi* Stanton; *c-e*, Gastropods: *c*. *Viviparus montanensis* Stanton; *d*, *Goniobosis* (?) *ortmanni* Stanton; *e*, *Campeloma harlowtonensis* Stanton.

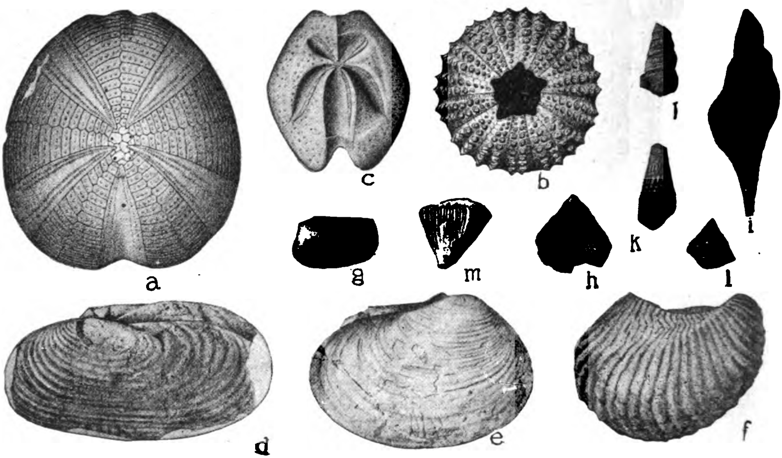



Fig. 449. Comanchean Fossils of the Texan Province. *a-c*, Echinoids: *a*, *Holaster simplex* Shum.; *b*, *Diplopodia texanum* Roemer; *c*, *Hemiaster dalli* Clark. *d-h*, Pelecypods: *d*, *Anatina austinensis* Vaughan; *e*, *Homomya austinensis* Vaughan; *f*, *Trigonia emoryi* Conrad; *g*, *Lima wacoensis* Roemer; *h*, *Pecten texanus* Roemer. *i-l*, Gastropods: *i*, *Fusus texanus* Vaughan; *j*, *Turritella budaensis* Vaughan; *k*, *Cerithium* (?) *texanum* Vaughan; *l*, *Trochus* sp.; *m*, a coral, *Parasmilia texana* Vaughan.

**Marine faunas.** Two very distinct marine faunas are found in North America, that of the Mexican Gulf and that of the Pacific

Coast. The former had its connections eastward with Portugal and the Mediterranean region; the latter, northward and westward with Asia and Russia, though the boreal element is less conspicuous in the upper part (Horsetown). No species common to the two provinces is known. The decline of the boreal aspect of the western

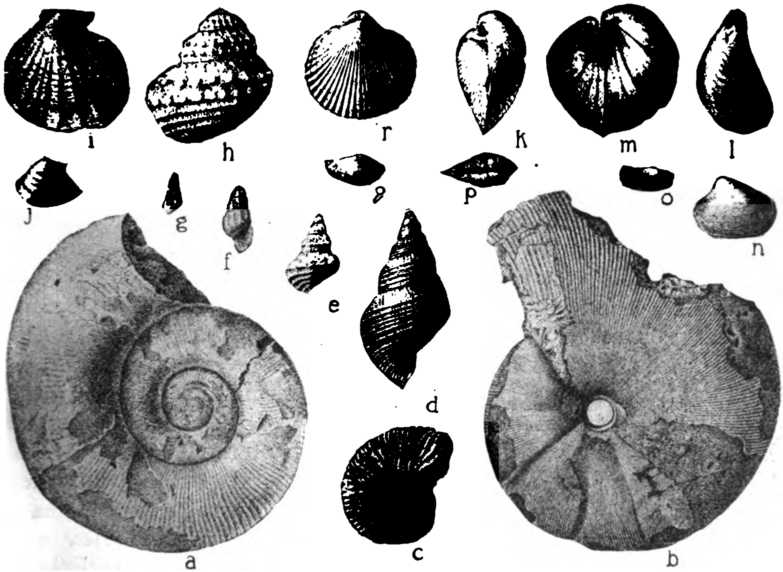



Fig. 450. Fossils from the Shastan Series (chiefly Knoxville). *a-c*, Cephalopods: *a*, *Lytoceras batesii* Trask; *b*, *Phylloceras knoxvillensis* Stanton; *c*, *Hoplites angulatus* Stanton. *d-h*, Gastropods: *d*, *Astrcsius liratus* Gabb; *e*, *Amberleya dilleri* Stanton; *f*, *Cerithium paskentaensis* Stanton; *g*, *Hypsipleura gregaria* Stanton; *h*, *Turbo moyonensis* Stanton. *i-q*, Pelecypods: *i*, *Pecten complexicosta* Gabb; *j*, *Corbula* (?) *persulcata* Stanton; *k* and *l*, *Aucella piochii* var. *orata* Gabb; *m*, *A. crassicollis* Keyserling; *n*, *Astarte californica* Stanton; *o*, *Arca tehamaensis* Stanton; *p*, *Nucula storrsi* Stanton; *q*, *Leda glabra* Stanton; *r*, *Rhynchonella whitneyi* Gabb, a brachiopod. (After Stanton.)

fauna may have been due to the closing of Bering Strait, thus shutting off cold currents from the Arctic.[1] The Comanchean faunas are said to represent three distinct facies, the *reef* facies, most conspicuous, the *littoral*, and the *deeper* water facies.

[1] Stanton, Jour. Geol., Vol. XVII.

# CHAPTER XXV

## THE CRETACEOUS PERIOD

### FORMATIONS AND PHYSICAL HISTORY

The Cretaceous period was ushered in, so far as North America is concerned, by a notable encroachment of the sea. Cretaceous formations are found in (1) the Atlantic Coastal Plain; (2) the Coastal Plain of the Gulf; (3) the Great Plains, from the Gulf of Mexico to the Arctic Ocean; (4) at many points in the western mountains; and (5) over considerable areas along the Pacific coast. While its distribution has much in common with that of the Comanchean, it is much more widespread (Fig. 451), and unlike the Comanchean, this system is chiefly marine.

**Atlantic border region.** Cretaceous formations come to the surface in a belt near the western margin of the Atlantic Coastal Plain (Fig. 451), just east of the outcrop of the Potomac series. The beds have been but little disturbed, and still dip, as when deposited, slightly to seaward, and in that direction pass beneath younger formations. They are largely of unindurated clay and sand, with some greensand marl, which is rather characteristic of the system. The distinguishing constituent of this marl is *glauconite*, primarily a hydrous silicate of potassium and iron,[1] which occurs in grains. Glauconite is now making in some parts of the sea, and from the situations in which it is formed, it is inferred that the conditions necessary for its development on such a scale as to make considerable beds, are the following:[2] (1) Water of moderate depth, 100 to 200 fathoms being the most favorable; (2) a meager supply of land-derived sediment; and (3) the presence of foraminifera. The production of the glauconite seems to be effected by

[1] Most Glauconite is impure, and, as it occurs in nature, contains several other ingredients.

[2] For brief summary concerning the origin of greensand marl, see Clark, Jour. Geol., Vol. II, p. 161. For a fuller account, see Challenger Report on Deep Sea Deposits.

Fig. 451. Map showing the distribution of the Cretaceous formation in North America. The conventions are the same as in preceding maps.

chemical changes in sediments perhaps as the result of decomposition of the organic matter contained in the foraminiferal shells.

The subdivisions now generally recognized are the following, commencing with the lowest: 1. *Matawan* formation; 2. *Monmouth* formation; 3. *Rancocas* formation; 4. *Manasquan* formation. These formations are not all continuous throughout the coastal region, and all the formations show notable variations when traced along their strikes. Their aggregate thickness nowhere exceeds a few hundred feet.

**Eastern Gulf border.** The outcrop of the Cretaceous formations of the eastern Gulf states is shown in Fig. 452. Near the Missis-

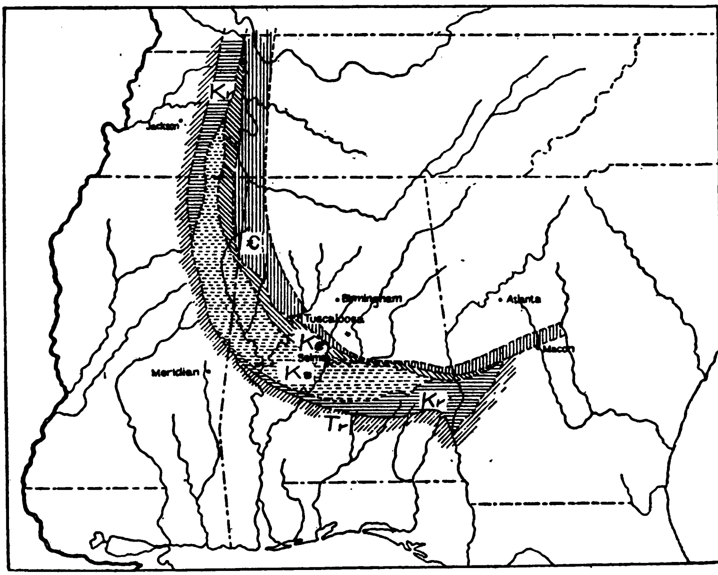



Fig. 452. Map showing the positions of the several members of the Comanchean and Cretaceous systems in Alabama and adjacent states. *C*, Tuscaloosa series (Comanchean); *Ke*, Eutaw formation; *Ks*, Selma chalk; *Kr*, Ripley formation; *Tr*, Tertiary. (After Smith.)

sippi, the belt of outcrops extends northward to Kentucky. Meager remnants (*outliers*) are found even north of the Ohio, in southern Illinois.

In Alabama, where the Gulf Coast part of the system is best known, there are three principal divisions: the *Eutaw* below

(mainly clays and sands, some greensand, 300 feet), the *Selma Chalk* (1,000 feet) in the middle, and the *Ripley* (mainly sand, 200–500 feet) above. The Eutaw is believed to be the equivalent of the Matawan formation of the Atlantic coast, and the Ripley is thought to be older than the Rancocas. The Cretaceous beds of the Gulf coast have been disturbed more than the corresponding beds along the Atlantic coast. They have been bent into low anticlines and synclines in some places (Alabama), and faulted to a slight extent.

**Western Gulf region.** The general stratigraphic relations of the system here are the same as farther east, but deposition seems to have been well under way in Texas before the oldest exposed beds of the system farther east were laid down. The system has a maximum thickness of about 4,000 feet. Three principal subdivisions are recognized: (1) The *Dakota*; (2) the *Colorado*; and (3) the *Montana*. The Dakota formation, 600 feet and less thick, is largely of sandstone, with some lignite, and is, for the most part, of non-marine origin. The Colorado series contains much limestone (or chalk) of marine origin. Its thickness is about 1,000 feet. The Montana series is more largely clastic, and from it the oil of the Corsicana oil field of Texas is derived. Locally, the system is much faulted. From Texas it is continued northward into Arkansas, and westward into New Mexico.

The Cretaceous of the western Gulf region differs from the corresponding system farther east in its greater thickness, and in its greater proportion of calcareous matter, largely in the condition of chalk. Of limestone or chalk, the Cretaceous of the Atlantic coast contains little, that of the eastern Gulf region (Alabama and Mississippi) more, and that of Texas much; nor is the chalk confined to the Gulf region, as will be seen.

**Western interior.** One of the standard sections of the Cretaceous system of the western interior consists of the following subdivisions, commencing at the bottom: 1. *Dakota*; 2. *Colorado* (including the Benton and the Niobrara formations); 3. *Montana* (including Ft. Pierre and Fox Hills); and 4. *Laramie.* This classification, however, does not fit all parts of the west.

The *Dakota formation*, mainly of non-marine origin, is widespread in the Great Plains, though most of it is buried. It extends westward beyond the Rocky Mountains at many points. The formation is largely sandstone, though it contains much conglomerate and clay, and some lignite. It is perhaps to be regarded as

the joint product of subaërial and fluviatile deposition. The presence of bird tracks in Kansas, and the widespread abundance of fossil leaves of angiosperms, in a condition which precludes much transportation, imply subaërial sedimentation to a notable extent at least. The upper part of the formation carries some marine fossils. North of Texas the formation is in apparent conformity with the Comanchean in some places, though in others it rests on older formations.

The Dakota sandstone is an important source of water in the semi-arid plains. The water enters where the sandstone outcrops near the mountains, and follows the beds down their dip to the eastward. Along the east base of the Rocky Mountains, where the beds

Fig. 453. A group of concretions weathered out from the Dakota sandstone. Near Minneapolis, Kan. (Schaffner.)

have been tilted, the less resistant formations associated with this sandstone have been removed or worn down, leaving the outcropping edges of this formation as ridges or "hogbacks" (Fig. 93), characteristic of the east base of the Rocky Mountains much of the way from New Mexico to Canada.

The *Colorado series* records an extensive invasion of the western

interior by the sea, the invasion going so far, probably, as to establish connection between the Gulf of Mexico and the Arctic Ocean, over the site of the Great Plains. Clastic formations predominate in the Colorado series as a whole, but there are beds of chalk comparable to those of Europe, from Texas to South Dakota. The aggregate thickness of the series is locally as much as 3,000 feet, as strata are measured, though its average thickness is much less.

*The origin of chalk.* There has been much difference of opinion concerning the origin of chalk. Its resemblance to the foraminiferal ooze of the deep seas long since led to the belief that it was a deep-sea deposit; but closer examination has thrown doubt on this conclusion, for the differences between the chalk and foraminiferal ooze are as striking as their likenesses. Both consist largely of the shells of foraminifera, but with them are associated shells of other types. The echinoderms, the sponge spicules, and the secretions of certain microscopic plants of the chalk correspond in a general way with those of the oozes now forming, and are consistent with the deep-water origin of the chalk. The molluscan shells of the chalk, on the other hand, seem to point with clearness to water no more than 30 to 50 fathoms deep. The distribution of the chalk and its relations to other sedimentary beds indicate its deposition in shallow water, not in water comparable in depth to that in which oozes are now formed. On the whole, the balance of evidence is in favor of the view that the Cretaceous chalk was deposited in relatively shallow water. The conditions for its origin seem to have been clear seas, with a genial climate. Its materials may accumulate as well on the bottom of a shallow sea as on the bottom of a deep one, if clastic sediments are absent.[1]

Following the Colorado epoch there were changes in the sedimentation and in the life of the western interior sea. The *Montana series* is chiefly clastic, but the area of sedimentation was somewhat contracted. The beds are largely marine, and the water shallowed as the epoch progressed. Land formations also are found in the series. Local beds of coal give evidence of marshy conditions. Like other parts of the system, the Montana series abounds in concretions, some of which attain great size. The thickness of the series is variable, and its maximum is great. From 8,700 feet in Colorado, it thins to 200 feet in some parts of the Black Hills.

Deposition continued in the Great Plains and to some extent

[1] For fuller statement of this subject see Earth History, Vol. III, p. 149.

west of them through the last epoch of the Cretaceous period, but most of the sedimentation was non-marine. Fresh-and-brackish-water beds are widely distributed.

The *Laramie series* records the transition from the marine conditions of the Montana epoch to the fresh-water and land conditions of the Tertiary in the same region. This change did not take place everywhere at the same time. The series consists primarily of sandstone and shale, with some conglomerate; but with these clastic formations there is much coal. Both shale and coal are more abundant below than above, while in the upper part of the series conglomerate is not rare. The thickness of the Laramie series is estimated at 1,000 to 5,000 feet, exclusive of the transition (Mesozoic-Cenozoic) beds to be mentioned below. In not a few places there is an unconformity in the great group of strata formerly classed as Laramie, and there is difference of opinion as to whether the part above this unconformity should be called Laramie. The present tendency is to regard it as Eocene.[1]

In a considerable area of northeastern Wyoming, and in a large area farther north, some of the Laramie lignite has been burned in the ground. The burning was relatively recent, and locally is still in progress. The firing appears to have taken place at the outcrops on hill and valley slopes. The burning was accompanied by fusion, semi-fusion, and baking, resulting in lava-like slag and brick-red banks of indurated clay.

*Coal.* The Cretaceous is pre-eminently the coal period of the west. Coal-beds occur in every one of its principal divisions in this part of the continent. The total amount of coal, chiefly in the Laramie, is perhaps comparable to that in the Pennsylvanian system, though the coal is not now so accessible, and its quality not so good. It is estimated that along the east and west bases of the Rocky Mountains there are more than 100,000 square miles of coal-bearing lands, and Colorado alone is estimated to have 34,000,000,000 tons of available coal,[2] most of which is Cretaceous. The coal is largely lignite, though in Colorado not a little of it has been advanced to coking bituminous coal, and even to anthracite, where

[1] The Laramie question is well reviewed by Cross, Washington Acad. of Sci., Vol. XI, pp. 27–45, 1909. Other recent discussions by Veatch are found in Am. Jour. Sci., Vol. XXIV, (1907), p. 18, and Jour. Geol., Vol. XV, 1907. See footnote p. 539.

[2] Storrs, 22d Ann. Rept., U. S. Geol. Surv., Pt. III.

it has been affected by intrusions of igneous rock. The areas of Laramie coal are indicated in Fig. 438.

*Transition beds between Mesozoic and Cenozoic.*[1] There are divers, more or less local, terrestrial formations in the west which have been referred now to the Cretaceous (Laramie,—or more exactly, to the upper Laramie or post-Laramie), now to the Tertiary

Fig. 454. An outcropping ledge of clay, hardened by the burning of the coal-bed below. Except in the immediate vicinity of the burnt-out coal-bed, the clay is not indurated. Near Buffalo, Wyo. (Blackwelder.)

(Eocene). These formations are, generally speaking, unconformable on the Laramie, and in some places seem hardly separable from the recognized Tertiary[2] (*Fort Union*). Their reference to the Eocene seems to be justified both on stratigraphic and paleontologic grounds, so far as present data are concerned.

**Pacific coast.** The Cretaceous system is represented on the

[1] The questions involved in the formations here referred to are discussed in the following recent papers: Stanton, Am. Jour. Sci., Vol. XXX, and Wash. Acad. Sci. Vol. XI; Knowlton, Wash. Acad. Sci., Vol. XI, and Am. Jour. Sci., Vol. XXXV; Stone and Calvert, Econom. Geol., Vol. V; Lee Am. Jour. Sci., Vol. XXXV; and Cross, Wash. Acad. Sci., Vol. XI.

[2] Here belong the Arapahoe, Denver, Raton, Monument Creek and perhaps other beds of Colorado, the Carbon, Evanston, and Lance (Ceratops) beds of Wyoming, and the Lance formation, and part of the Livingston beds of Montana.

Pacific coast by the marine *Chico* series. At the time of its origin, this series probably extended along the coast from Lower California to the Yukon. The Chico series rests on the Shastan unconformably in some places, and overlaps it at others. The fauna of the Chico series is littoral. Its oldest portion is older than the fauna of the Colorado series, and its youngest is older than the fauna of the youngest Cretaceous beds.

### *Close of the Period*

About the close of the Cretaceous period a series of disturbances was inaugurated on a scale which had not been equaled since the close of the Paleozoic era. These changes furnish the basis for the classification which makes the close of this period the close of an era. These disturbances continued into later times, but the close of the Cretaceous may be said to have been the time when the changes had advanced so far as to make themselves felt profoundly. They consisted of deformative movements, a part of which were orogenic, and of igneous eruptions on an almost unprecedented scale.

**General movements.** In the closing stages of the period, the sea which had lapped over the Coastal Plains of the Atlantic and


Fig. 455. Section showing the position of the Cretaceous beds in western Oregon. *Mg*, meta-gabbro of unknown age; *sp*, serpentine; *as*, amphibolite schist; *Jr*, Jurassic (?); *Km* and *Kmw*, Cretaceous; *Eu*, Eocene; *Ed*, Eocene diabase. (Diller, Roseburg, Ore., folio, U. S. Geol. Surv.)

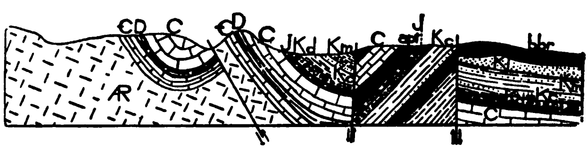



Fig. 456. Section showing position of Cretaceous beds at one point in the vicinity of Livingston, Montana. *Æ*=Archean; Є, Cambrian; *D*, Devonian; *C*, Carboniferous; *J*, Jurassic; *Kd*, Dakota formation; *Kc*, Colorado series; *Km*, Montana series, and *Kl*, Laramie series; *bbr*, basic igneous rock, and *apt*, acidic rock. Length of section about 11 miles. (Livingston, Mont., folio, U. S. Geol. Surv.)

the Gulf of Mexico was withdrawn toward the abysmal basin. At about the same time, the Appalachian Mountains, which had been reduced to a peneplain by this time, were bowed up again.

It is probable that most of the Cordilleran region was elevated

bodily at this time, though not to a great height. Without further details, it may be said that enough is known to make it probable that a large part of the continent was affected by deformative movements of a gentle sort.

**Orogenic movements.** The growth of mountains by folding probably was in progress in the closing stages of the Cretaceous period from Alaska on the north to Cape Horn on the south,— more than a quarter of the circumference of the earth. At the same time folding movements probably affected the Antillean mountain system,[1] between the southern end of the Cordilleran and the northern end of the Andean systems, for in several of the Antillean islands later formations rest unconformably on the deformed Cretaceous beds. Where the Eocene rests conformably on the Laramie, the disturbances of this time are not clearly distinguishable from those of later date, which increased the folding initiated in this epoch. Some of the folded ranges of the western mountains began their history at this time, others had a new period of growth, and still others date from a later time; yet the close of the Laramie was a time of general orogenic movement in the western part of North America. The Rocky Mountain system may be said to have had its birth at this time. That these mountains are not older is shown by the deformation of the Laramie beds along with those of greater age. That some of the folding was not younger is shown by the lesser deformation of the Tertiary beds in the same region.

**Faulting.** The growth of mountains at the close of the Cretaceous was accompanied by faulting on a somewhat extensive scale throughout the region of movement, though the faulting of this time

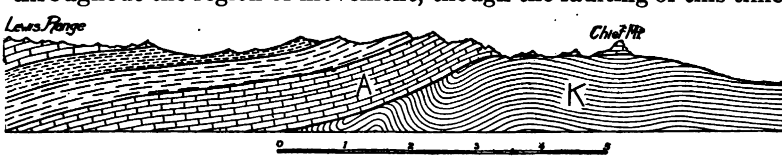



Fig. 457. Section in northern Montana, showing Proterozoic rock, *A*, thrust over Cretaceous, *K*. Subsequent erosion has removed much of the overthrust beds, but Chief Mountain is a remnant of them.

cannot be distinguished everywhere from that of later date. In the Rocky Mountains of British Columbia, one overthrust fault has been located which crowded the Cambrian rocks obliquely up over the Cretaceous. The horizontal displacement is estimated to be

[1] Hill, Nat. Geog. Mag., Vol. VII, p. 175.

as much as seven miles,[1] and the throw 15,000 feet. Near the national boundary, the displacement along what appears to be the same fault crowded the Proterozoic up over the Cretaceous [2] by a movement of equal magnitude (Fig. 457). The exact date of these faults has not been determined, but was, perhaps, mid-Tertiary.

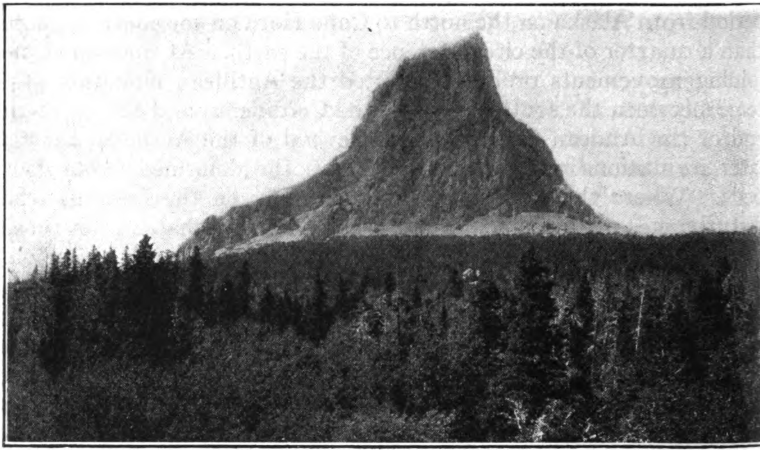


Fig. 458. Chief Mountain. (Willis, U. S. Geol. Surv.)

**Igneous eruptions.** The close of the Cretaceous was marked by the inauguration of a period of exceptional igneous activity, continuing far into the Tertiary. During this period, great bodies of igneous rock, both extrusive and intrusive, were forced up. Eruptions occurred in other lands at about the same time.

### *Upper Cretaceous of Other Continents* [3]

**Europe.** The distribution of the Upper Cretaceous strata of Europe shows that extensive transgressions of the sea occurred at the beginning of the period, for in some parts of the continent marine Cretaceous formations overlap all older Mesozoic systems. During the closing stages of the Upper Cretaceous, fresh-water beds

[1] McConnell, Geol. Surv. of Canada, Vol. II, Rept. D, p. 33, 1886.
[2] Willis, Bull. Geol. Soc. of Am., Vol. XIII, pp. 307, 331–335.
[3] The term Comanchean has not been applied outside of North America, and the Cretaceous system will therefore be referred to as Upper Cretaceous.

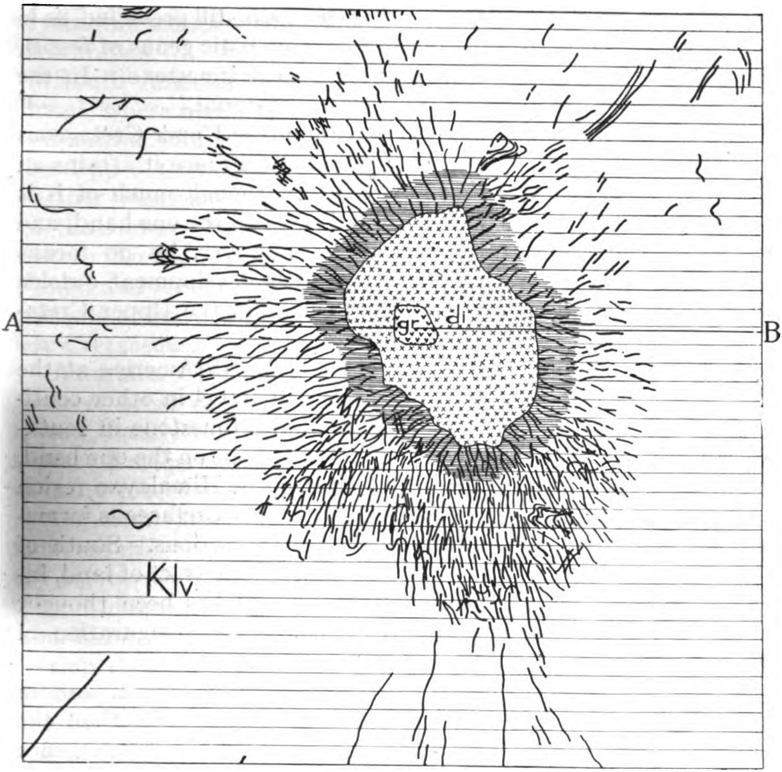




Fig. 459. Map and section showing relations of igneous rock to the Cretaceous formations in the Crazy Mountains of Montana. The section is along the line *AB* of the map. *Klv*, Livingston formation; *di*, diorite; *gr*, granite. The especial feature of the map is the extraordinary number of dikes radiating from the central intrusion, *di*. Length of section about 20 miles. (Livingston and Little Belt, Mont., folios, U. S. Geol. Surv.)

appear in localities (Alpine region) where marine sedimentation had been in progress earlier in the period, showing that the movements which were to mark the close of the era were making themselves felt. Limestone is the dominant sort of rock in the Upper Creta-

ceous of southern Europe, showing that clear seas still prevailed, as in the Early Cretaceous period. From a characteristic genus of fossils, much of the limestone is known as *Hippurite* limestone. In the system farther north, there is more clastic material.

The most notable petrographic feature of the Upper Cretaceous of Europe is the chalk. Both in England and France it attains an aggregate thickness of several hundred feet, though much of it is far from pure. It grades into marls and clays on the one hand, and into sandstone on the other. Chalk is, however, by no means co-extensive with the system, for it has little development outside of the Anglo-French area. Greensand occurs in the Upper Cretaceous as well as in the Lower.

**Asia.** The submergence of Europe and North America at the beginning of the Upper Cretaceous finds its parallel in other continents. There are extensive areas of Hippurite limestone in southwestern Asia, closely connected with that of Europe on the one hand, and with that of North Africa on the other. The Himalayan region seems to have been still beneath the sea, for Upper Cretaceous formations are found in the mountains at great elevations. South of these mountains there appears to have been a large tract of land, including much of the peninsula of India, which has been thought to have stretched southwest to Africa; but the configuration of the sea-bottom does not lend this view much support.

Upper Cretaceous beds occur on the coast of China, and in Japan. In many places they rest on formations older than the Lower Cretaceous, and therefore record an increased submergence dating from the beginning or early part of the Upper Cretaceous. On the other hand, northern Asia, which was largely submerged during the earlier Cretaceous period, was largely land during the later. Late in the Upper Cretaceous occurred the extensive lava-flows of the Deccan. These flows, 4,000 to 6,000 feet in thickness, cover an area of something like 200,000 square miles, and are the most stupendous outflows of lava recorded. The fossils in sediments interbedded with the lava show that the flows were subaërial.

**Africa.** In northern Africa, the Upper Cretaceous beds overlie the Lower unconformably, and spread southward, covering most of the desert, and so indicating great submergence in the north African region. South of the Sahara, no Upper Cretaceous beds are known except in a few small areas about the coast, where they rest on

crystalline schists with no Lower Cretaceous beds beneath, so far as now known.

**South America.** In South America the sea invaded eastern Brazil, where marine Upper Cretaceous beds cover and overlap the non-marine Lower Cretaceous. In some parts of Brazil, however, the Upper Cretaceous is represented by fresh-water beds only. Farther west, marine Upper Cretaceous beds rest unconformably on the Lower Cretaceous, and form the summits of parts of the eastern Andes, occurring up to altitudes of 14,000 feet at many points, and locally even higher. There appears to have been great volcanic activity in the Andean system (Chile and Peru) during the late Cretaceous.

**Australia.** The phenomena of Australia are in harmony with those of other continents. The Upper Cretaceous beds are widespread, locally resting on formations older than the Lower Cretaceous. Furthermore, the Upper Cretaceous (*Desert sandstone*) is in many places unconformable on the deformed Lower Cretaceous.

**General.** In general it may be said that there was little marine sedimentation in the Late Cretaceous period north of the parallel 60° north, where the Jurassic and Lower Cretaceous systems are more widespread. Between the parallels of 20° and 60°, on the other hand, the zone where marine Lower Cretaceous is but slightly developed, the Upper Cretaceous system is widespread. Outside of China, the Upper Cretaceous system is wanting over no considerable land-area within these limits. In the equatorial and south temperate zones, the Upper Cretaceous seas were also expanded much beyond the limits of the waters of the preceding period.

## *Climate*

The climate of North America throughout most of the Cretaceous period seems to have been rather uniform and warm through a great range of latitude. In Greenland, Alaska, and Spitzbergen, climatic conditions seem to have been similar to those in Virginia. Toward the close of the period the temperature was perhaps lower, for the Laramie flora is a temperate, rather than a tropical, one. The fresh-water fossils of central Europe indicate a climate comparable to that of Malaysia. As this seems to have been a period of low land, widely extended epicontinental seas, extensive calcareous deposits, and slow consumption of carbon

dioxide in the carbonation of rock, there was a combination of conditions regarded as favorable for a mild and uniform climate.

## LIFE

**Land plants.** Angiosperms predominated in North America at the beginning of the Cretaceous, and during the period genera now living came to be numerous, giving the flora a modern aspect. Among the living genera which made their appearance were those which include the birch, beech, oak, walnut, sycamore, tulip-tree, and maple. Among the gymnosperms there was a notable development of the sequoias, which now include the giant trees of California. Of special interest was the presence of genera in Europe and the United States which are now confined to the southern hemisphere.

Toward the close of this period, monocotyledons first became abundant, so far as the record shows. *Palms* were plentiful, even in northerly latitudes, before the close of the period. Of greater importance because of their relations to the evolution of grazing animals, was the appearance of *grasses*, which attained prominence later.

It is worthy of remark that the introduction of dicotyledons, the great bearers of fruits and nuts, and of monocotyledons, the greatest grain and fodder producers, was the groundwork for a profound evolution of land animals. A zoölogical revolution, as extraordinary as the botanical one, might naturally be anticipated; but it did not follow immediately, so far as the record shows. The reptiles seem to have roamed through the new forests as they had through the old, without radical modification. But with the opening of the next era, the anticipated revolution in the animal life of the land made its appearance, and advanced with great rapidity.

The new flora spread widely. The European flora was very much like the American, and there was a close resemblance between the plants of mid-Greenland (70°–72° Lat.) and those of Virginia, indicating climatic conditions of remarkable uniformity. Not only this, but the flora was of a sub-tropical type.

**Land animals.** The terrestrial animals had the same general aspect as in the preceding period. *Dinosaurs* still retained the leading place among land reptiles, though carnivorous forms were less abundant and varied than before. Among them was a leaping, kangaroo-like form with a length of 15 feet. The most singular

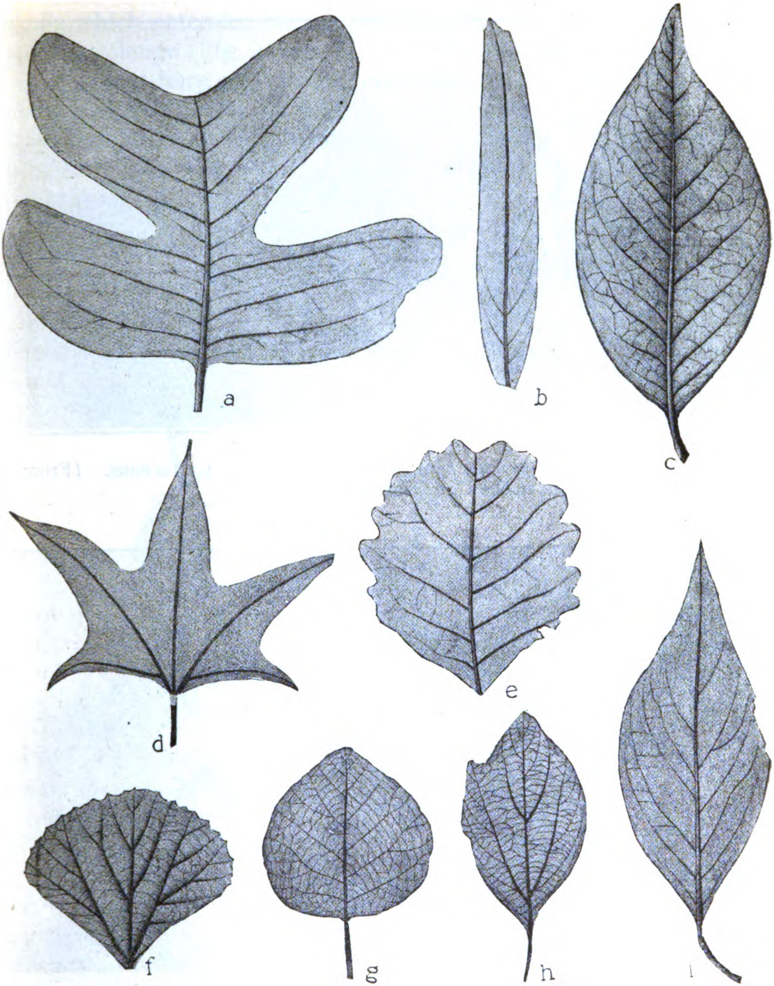



**Fig. 460.** GROUP OF FOSSIL LEAVES OF TYPICAL CRETACEOUS PLANTS FROM THE DAKOTA HORIZON. *a*, *Liriodendron giganteum* Lesq.; *b*, *Nyrica longa* Heer; *c*, *Magnolia pseudoacuminata* Lesq.; *d*, *Sterculia mucronata* Lesq.; *e*, *Quercus suspecta* Lesq.; *f*, *Viburnum inæquitaterale* Lesq.; *g*, *Betulites westi*, var. *subintegrifolius* Lesq.; *h*, *Sassafras subintegrifolium* Lesq.; *i*, *Ficus inæqualis* Lesq.

dinosaurian development was in the herbivorous branch. Some of the forms were very large, of quadrupedal habit, with enormous

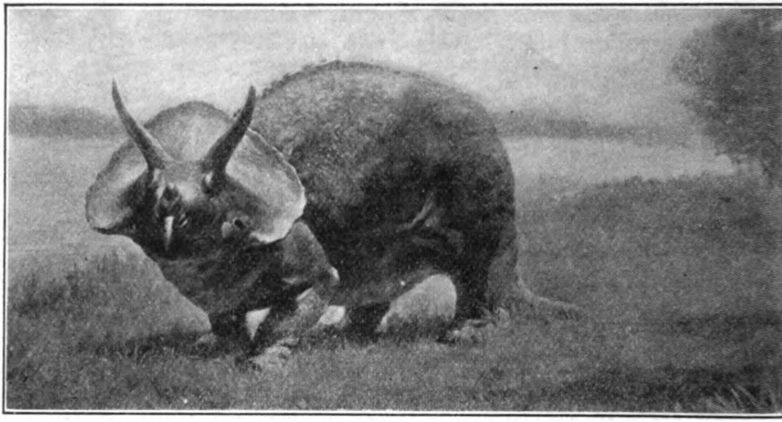


Fig. 461. *Triceratops prorsus* Marsh, from the Laramie Cretaceous. (From a painting by C. R. Knight in the U. S. National Museum.)

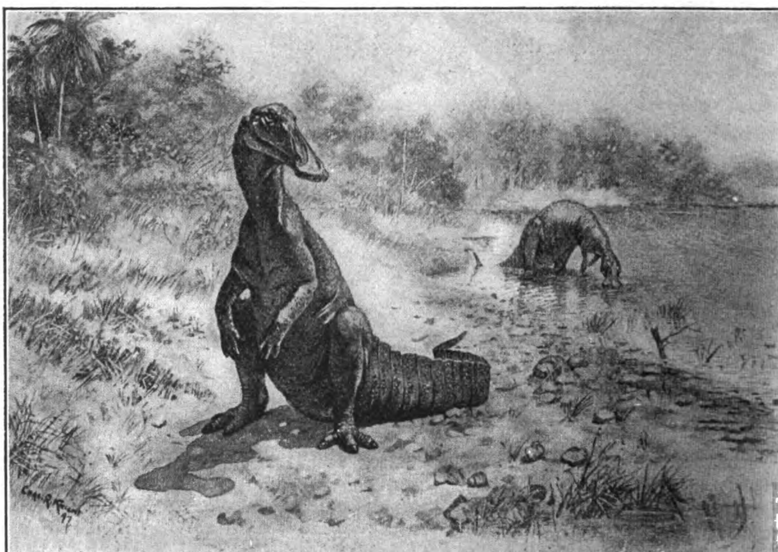


Fig. 462. Spoonbill Dinosaurs of the Cretaceous *Hadrosaurus mirabilis* (Leidy) as interpreted by Knight. (Osborn, Copyrighted by the Am. Mus. of Nat. Hist.)

skulls which extended backwards over the neck and shoulders in a cape-like flange (Fig. 461). Added to this was a sharp, parrot-like beak, a stout horn on the nose, and a pair of large pointed horns on the top of the head. One of the larger skulls measures eight feet from the snout to edge of the cape. This excessive provision for defense was accompanied by a very small brain cavity. Marsh remarks that they had the largest heads and the smallest brains of the reptile race. They were doubtless stupid and sluggish. The ornithopod division was well represented (Fig. 463). Their hinder parts were large, their limbs were hollow, and their footprints indicate that they walked in kangaroo-like attitude.

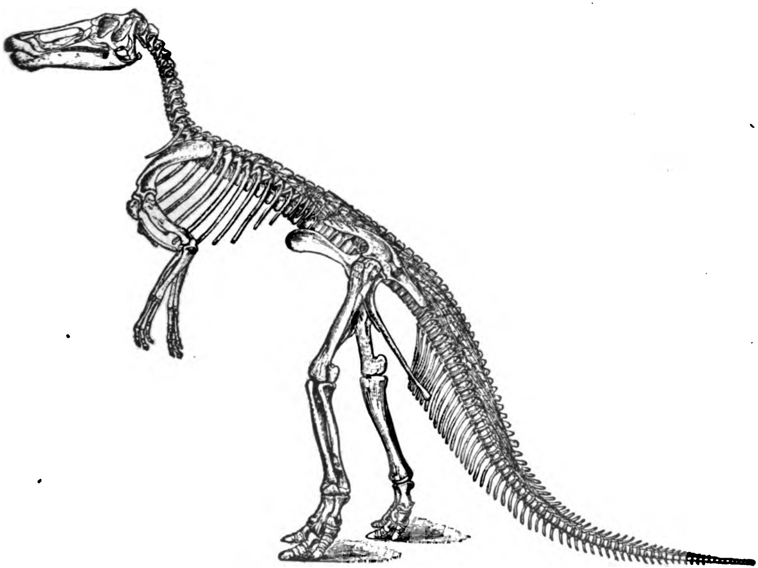


Fig. 463. A Cretaceous dinosaur of the ornithopod division, *Claosaurus annectens*. (Restored by Marsh.)

Terrestrial *turtle* remains are found in the Dakota sandstone, and the fossils of species inhabiting fresh waters in the late Cretaceous deposits of Canada. Of true *lizards*, only one late Mesozoic form is known, and that of small size and uncertain affinities, from the Laramie. *Snakes* made their first appearance, so far as known, in the later part of the period, but they were small. *Crocodiles* under-

went a marked change early in the period, developing into the modern forms, though some of the old types lived on.

*Flying reptiles* made so distinct an advance in specialization that Williston regards them as having come to excel all other flying

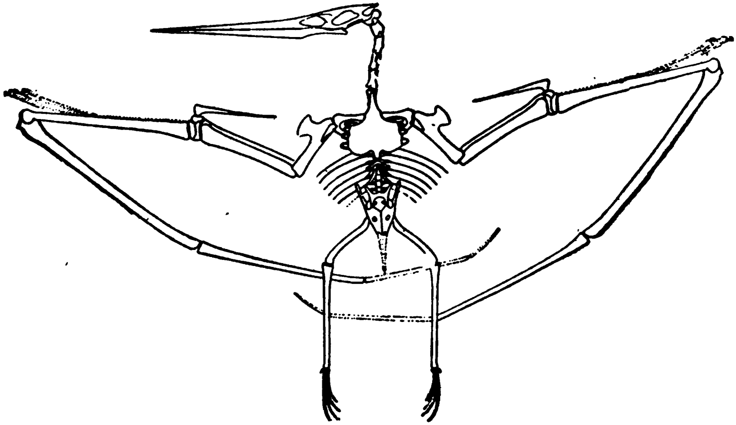


Fig. 464. A Cretaceous pterodactyl, *Nyctosaurus gracilis* Marsh, about 1/10 natural size, Niobrara Cretaceous, Kansas. (Restored by Williston.)

vertebrate animals. Some had a wing-spread of perhaps 20 feet. In some of the genera (Fig. 464) the development of the front parts was great, while the hind parts were so very small and weak that it is doubtful whether they could stand on their feet alone. The Cretaceous forms were all short-tailed, and for the most part toothless. Their bills resembled those of modern birds.

Terrestrial *birds* existed, but their record is meager. There were some curious aquatic forms, which will be mentioned with the sea life. The *mammals* thus far recovered from the Cretaceous

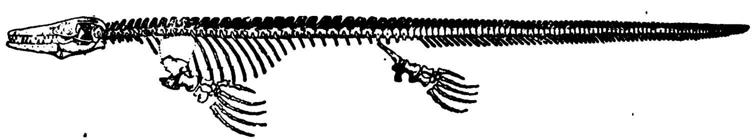


Fig. 465. A Cretaceous mosasaur, *Platacarpus coryphæus* Cope, restored by Williston; from Upper Cretaceous, Kansas.

indicate little advance on those of the Jurassic, and they appear to have played very little part in the fauna of the period.

**Sea life.** *Vertebrates.* The *ichthyosaurs* and *plesiosaurs* which

had dominated the Jurassic sea lived on into this period. The former became insignificant soon after its beginning; but the plesiosaurs attained their highest development and perhaps their greatest size at this time. The American plesiosaurs indicate lack of intermigration between this continent and Europe.

The aquatic branch of the scaled saurians (*Squamata*) became veritable sea serpents. The long-necked, lizard-like reptiles of the Comanchean period were the forerunners, and perhaps the direct ancestors, of a family (the *mosasaurians*, Fig. 465) which flourished in the Cretaceous, and ranged from the Americas to Europe and New Zealand. Their short career seems to have ended with the period, and no direct descendants are known.

Marine *turtles* seem to have appeared first in this period, and to have had many forms. Some of them had skulls larger than those of horses, and their shells must have been fully twelve feet across.

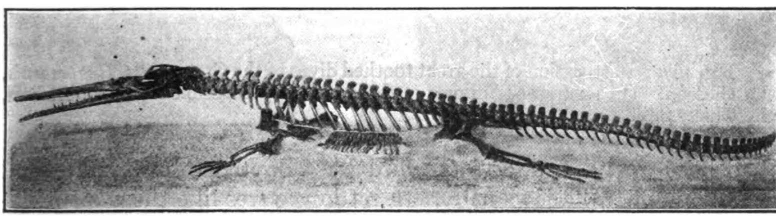


Fig. 466. *Champsosaurus*, from the Laramie of Montana. Length, about six feet. (After Brown.)

In the long interval between the first known appearance of *birds* in the Jurassic, and the later Cretaceous when they reappeared, important changes took place, among which was the loss of the elongate, bilaterally feathered tail. The Jurassic birds were terrestrial, while the Cretaceous were aquatic. The Cretaceous birds include about 30 species belonging to two widely divergent orders, *Hesperornis* and *Ichthyornis*. The former (Fig. 467) were large, flightless divers, with aborted wings and remarkable legs. The legs were not only very powerful, but the bones of the feet were so joined to them as to allow the feet to turn edgewise in the water when brought forward, thus increasing their efficiency as paddles. Furthermore, the legs were so joined to the body frame as to stand out nearly at right angles to it, like a pair of oars, instead of being under the body like walking legs. Apparently, walking as well as flying

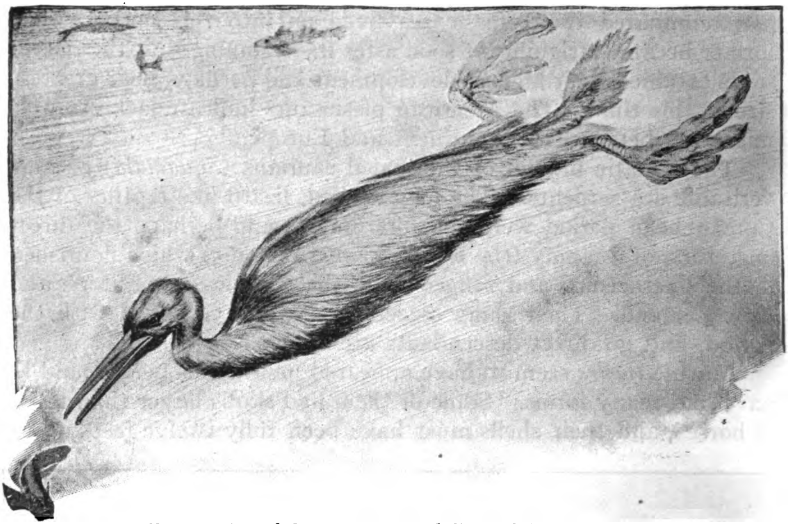


Fig. 467. Restoration of the great toothed diver of the Cretaceous, *Hesperornis*, by Gleeson. (From Lucas' Animals of the Past; by permission of the publishers, McClure, Phillips and Co.)

had been abandoned, and the bird was adapted to swimming and diving only. The jaws had teeth set in grooves like those of primitive saurians, and in other respects were like the jaws of snakes. As some of these strange birds attained a length of six feet, they were doubtless formidable enemies to the sea life on which they chose to feed. They have been found in Kansas, Montana, North Dakota, New Jersey, and England, and probably frequented epicontinental seas somewhat widely.

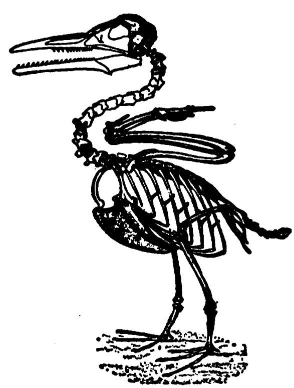
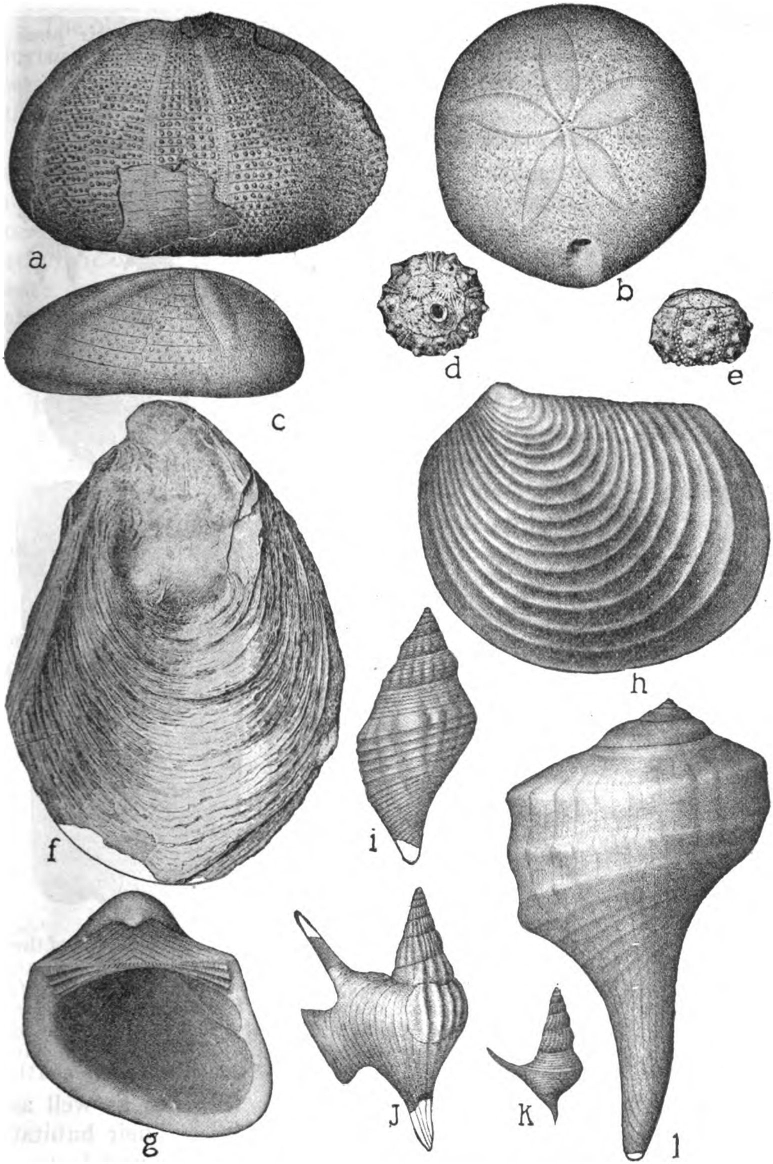


Fig. 468. *Ichthyornis victor*, a Cretaceous toothed bird of flight, 1/10 natural size. (Restored by Marsh.)

The second type *Ichthyornis* (Fig. 468) was scarcely larger than a pigeon, and had great power of flight, as indicated by the strong development of the wings and keel. At the same time, their legs and feet were small and slender. They had teeth in sockets.




For explanation of Figure, see top of page 554.

Fig. 469. CRETACEOUS FOSSILS. *a-e*, Echinoderms: *a*, ***Pedinopsis pondi*** Clark; *b*, ***Cassidulus subquadratus*** Con.; *c*, ***Botriopygus alabamensis*** Clark; *d* and *e*, ***Salenia tumidula*** Clark. *f*, *g*, and *h*, Pelecypods: *f*, ***Ostrea soleniscus*** Meek; *g*, ***Idonearca nebrascensis*** Owen, allied to the arcas of to-day; *h*, ***Inoceramus vanuxemi*** M. and H. *i-l*, Gastropods: *i*, ***Neptunella intertextus*** (M. and H.); *j*, ***Aphorrhais prolabiata*** (White); *k*, ***Drepanochilus nebrascensis*** (E. and S.); *l*, ***Pyropsis bairdi*** (M. and H.)

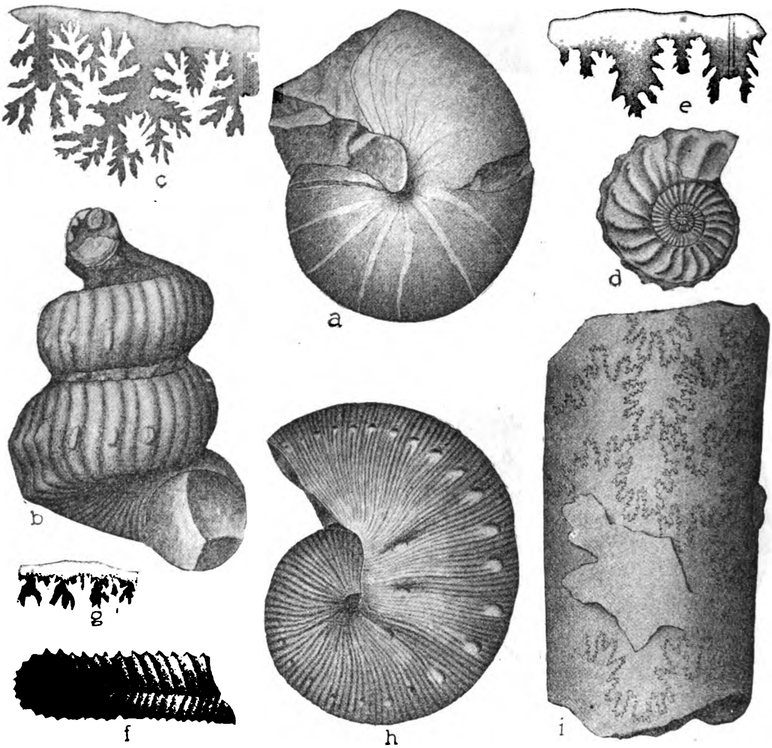



Fig. 470. CRETACEOUS CEPHALOPODS: *a*, *Nautilus meekanus* Whitf., one of the simplest types of closely coiled cephalopods; *b*, *Helicoceras stephensoni* Whitf., an ammonite coiled in a heliciform spiral, and *c*, its highly complicated suture; *d*, *Prionotropis woolgari* (Mantell), a normal ammonite with ornamented shell, and *e*, complex sutures; *f*, *Ptychoceras crassum* Whitf., an ammonite shell which is recurved upon itself, but not coiled; *g*, suture of *f*; *h*, *Scaphites nodosus* Owen, an ammonite showing as light tendency to uncoil in the last volution; *i*, *Baculites grandis* M. and H.

Their biconcave vertebræ and other skeletal features, as well as their small brains, suggest reptilian relationships. Their habitat was the same as that of Hesperornis, and yet the two were farther apart, structurally, than any two types of birds now living (Marsh).

The old types of fishes gave place to new ones (the teleosts) during this period. This change set in during the Comanchean, and was complete by the middle of the Cretaceous, though representatives of the older types lived on.

**Invertebrates.** The most notable departure from the preceding ages is the prominence of *foraminifers* among the fossils. They made large contributions to the chalk of the period, and they were concerned in the formation of the greensand, scarcely less characteristic of the period than the chalk. While some of these minute organisms live on shallow bottoms, on fixed algæ, and in abysmal water, they are chiefly inhabitants of the surface waters of the open sea.

**Sea-urchins** (*a–e*, Fig. 469) were quite abundant, and lent one of its characteristic aspects to the fauna. *Corals* and *crinoids*, so long associated with clear seas, were not plentiful. In the clastic formations, *pelecypods* (*f–h*) and *gastropods* (*i–l*) abound (Fig. 469). It will be seen by a glance at Fig. 469 that they have a modern appearance. *Cephalopods* were still abundant, though ammonites were in their decline and showed erratic forms, attended by excessive ornamentation, comparable to that which marked corresponding stages of the trilobites and crinoids. Odd forms of partial uncoiling, or of spiral and other unusual forms of coiling, were common (Fig. 470). Interesting forms, perhaps to be classed here, were the *Baculites* (*i*), which resumed the straight form of the primitive *Orthoceras*, while retaining the very complicated sutures of the *Ammonites* (*c*).

*Map work.* Folios of the U. S. Geol. Surv. and Laboratory Exercises in Structural and Historical Geology, Exercise XI. In the folios of the U. S. Geol. Surv. both Comanchean and Cretaceous are classed as Cretaceous, though the two are distinguished, in some cases, in the text and on the maps.

# THE CENOZOIC ERA

## CHAPTER XXVI

### THE EOCENE AND OLIGOCENE PERIODS

The remaining periods of geological history constitute the Cenozoic era, or the era of modern life. The earlier part of the era is called the Tertiary, and the later the Quaternary. The Tertiary is variously subdivided, as shown below:

| | | | | |
|---|---|---|---|---|
| Cenozoic Era | Quaternary | Recent or Human. Post-glacial formations<br>Pleistocene or Glacial. Glacial formations and non-glacial deposits of glacial age | | |
| | | I | II | III |
| | Tertiary | Pliocene<br>Miocene | Pliocene<br>Miocene | Neocene |
| | | Oligocene<br>Eocene | Eocene | Eocene |

#### FORMATIONS AND PHYSICAL HISTORY

There is much to be said for a two-fold division of the Tertiary, the first including the Eocene, Oligocene, and Early Miocene, and the second the later Miocene and Pliocene. This division differs from that of the right-hand column above only in putting the lower part of the Miocene in the lower division.

Eocene formations appear in widely separated parts of North America (Fig. 471), though they do not appear at the surface over large areas. They include marine formations, brackish-water formations (made in bays and estuaries), and land (lacustrine and subaërial) formations. The marine and brackish-water beds are confined to the borders of the continent, while the terrestrial deposits are found in the Great Plains and farther west. Many of the formations are not indurated, but locally they are even metamorphosed.

**The eastern coast.**[1] Eocene formations appear at the surface

[1] Dall, 18th Ann. Rept., U. S. Geol. Surv., Pt. II.

Fig. 471. Map showing the distribution of the Eocene formations in North America. The conventions are the same as in former maps.

in an interrupted belt near the coast from New Jersey to Texas. Their structure is similar to that of the Cretaceous system, upon

which they are unconformable (Fig. 446). Clays, sands, and green-sand marls are the most common materials of the system, and the conditions of sedimentation were much as in the preceding period.

The system is thicker (1,700 feet maximum) in the Gulf region than on the Atlantic coast. It contains much lignitic matter in places, showing that marine conditions were not uninterrupted. In Texas, gypsiferous and saliferous sediments recur at various horizons, though most of the beds are of marine origin, and there are numerous local unconformities in the system, suggesting repeated changes in the conditions of sedimentation.

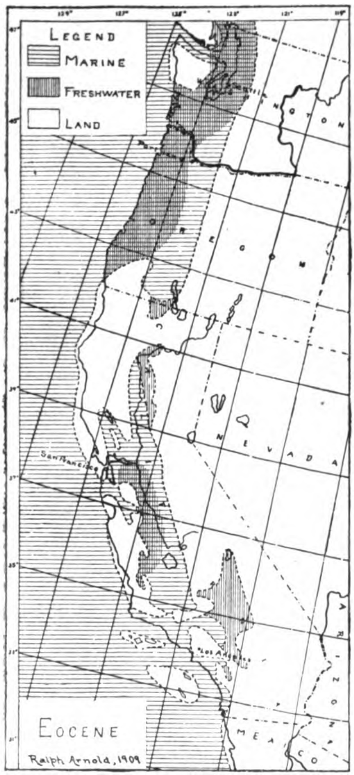



Fig. 472. Map showing supposed distribution of land and water on the Pacific coast of the United States during the Eocene period. (Ralph Arnold.)

**The Pacific coast. Marine and brackish-water beds.**[1] Marine Eocene formations are widespread west of the Sierra and Cascade ranges (Fig. 472), and have considerable development in Alaska. Throughout Washington and Oregon and in parts of California, the Eocene is unconformable on the Cretaceous (or Shastan), but in much of California it is conformable on the Chico, the plane between the two being defined by fossils. These relations suggest that just before the Eocene, all of Washington, most of Oregon, and parts of the coastal region of California were land, over which the sea advanced later. The rocks are mostly clastic, sandstone and shale predominating, but there are conglomerates, tuffs, and diatomaceous shales, the last thought to be a source of oil. In not a few places, marine beds are succeeded by brackish-water deposits.

[1] Arnold, Jour. Geol., Vol. XVII.

By the beginning of the Eocene, the Puget Sound depression, perhaps to be correlated with the great valley of California and the Gulf of California, had begun to show itself.[1] The lands east and west of the sound were high, but not mountainous; and the region of the sound was a great estuary, in and about which deposition was in progress. Some of the sediments accumulated in brackish water and on land, and resulted in the thick coal-bearing *Puget* series of Washington, the upper part of which is Oligocene or even Miocene. The series is said to contain 125 beds of coal thick enough to attract prospectors. Most of the workable coal is in its lower part. The area of deposition extended south into Oregon, and east toward the Blue Mountains of that state. The system has an estimated thickness of 10,000 to 12,000 feet in southern Oregon, and but little less in southern California.

British Columbia appears to have been land during the period, but Eocene beds, much disturbed (*Kenai* series), have been recognized in Alaska, where they are coal-bearing in places.

After the Eocene there was a time of temporary elevation, erosion, and volcanic activity along the Pacific coast, with considerable basaltic flows in Washington and Oregon.

**The western interior.** The warpings, faultings, and the intrusions and extrusions of lava which marked the close of the Mesozoic era in the west appear to have developed lands which were relatively high, adjacent to tracts which were relatively low. The steep slopes of the mountain folds, fault scarps, and volcanic piles seem to have afforded the conditions for rapid erosion, while the adjacent lowlands furnished places of lodgment for much of the sediment. Some of it took the form of fans and alluvial plains, and some of it probably lodged in lake basins formed by warping and faulting, or by the obstruction of valleys by lava flows. The wind also made its contribution to the deposits of the time, and the Eocene system contains much pyroclastic material. The result was a combination of lacustrine, fluvial, pluvial, eolian, and volcanic deposits.

The sites of principal sedimentation shifted somewhat from time to time, and among the widely distributed deposits referred to this period there are great differences of age. Several more or less distinct stages of deposition have been made out, the distinctions being based partly on the superposition of the beds, and partly

[1] Willis, Tacoma folio, U. S. Geol. Surv.

on their fossils. These several stages are not readily correlated with those of the coasts.

1. Reference has been made (p. 539) to certain formations (Denver, Raton, Lance, etc.), formerly classed as Cretaceous, which probably should be regarded as early Eocene. Some of these beds are inseparable from the *Fort Union* formation (or series), commonly regarded as the oldest division of the Tertiary in the western interior. During the Fort Union stage, there was an extensive area of aggradation in parts of North Dakota[1], Montana, and farther north.

The Fort Union beds are clastic and are said to be locally 2,000 feet or more thick. Parts of the formation may be lacustrine, but parts are subaërial[2] as indicated by the abundance of leaves at many places. The Fort Union series contains much coal, including some that was formerly classed as Laramie. Eocene formations of similar age are found in Colorado (*Telluride* and *Poison Canyon* formations), New Mexico (part of the *Puerco* beds), and elsewhere.

The sites of early Eocene deposition were finally shifted. In so far as the sedimentation was in lakes, the basins may have been filled or warped out of existence, and in so far as it was subaërial, deformative movements, or the progress of the gradational work of the streams, or both, may have been responsible for the shifting.

2. During the next or *Wasatch stage* of the period, sediment was being deposited over parts of Utah, western Colorado, and Wyoming, and elsewhere. The beds of this stage have a maximum thickness of several thousand feet, and are now 6,000 to 7,000 feet above the sea. About 77% of the fossils are of land life.

3. The third recognized stage of the Eocene in this region is the *Bridger*, during which sedimentation was in progress in the Wind River basin north of the mountains of that name, and another, a little later, in the basin of the Green River, both in Wyoming, and in Utah south of the Uinta Mountains. It may have been during this stage, too, that the volcanic tuff (*San Juan* formation, 2,000 feet and less thick) of southwestern Colorado was made. This last formation is of interest as an index of the vigor of volcanic action in this region. Beneath it, glacial drift was found in 1913 by Professor Atwood. Its extent is undetermined, and it maybe

[1] Wilder. Jour. Geol., Vol. XII, p. 290, and Leonard, State. Geol. Surv. of North Dakota, Fifth Biennial Rept.

[2] For criteria for distinguishing lacustrine and subaërial formations, see Davis, Science, N. S., Vol. VI, p. 619, 1897, and Proc. Am. Acad. Arts and Sci., Vol. XXXV, p. 345, 1900.

older than the Bridger Stage. It is at the base of the Eocene in this locality, near Ridgway.

4. The *Uinta stage* followed the Bridger. Deposition was then in progress in southeastern Utah and southwestern Colorado. Some of the Uinta beds now have an altitude of as much as 10,000 feet, though they probably were deposited at a much lower level.

**The northwest.** In the northwest there are Eocene formations not definitely correlated with the preceding stages. In northern Oregon, there are late Eocene beds of terrestrial origin (*Clarno* formation, largely volcanic tuff). In Washington, two thick sedimentary formations (the *Swauk*, early Eocene, 3,500–5,000 feet, below, and the *Roslyn*, 3,500 feet) of Eocene age and non-marine origin, are separated by 300–4,000 feet of basalt. The *Payette* formation of Idaho, said to have been accumulated in a lake formed by the damming of the upper basin of the Snake River by the early lava-flows of the Columbia River region,[1] is now referred to the Eocene. Eocene beds of terrestrial or volcanic origin are imperfectly known in many other places west of the Rocky Mountains. The erosion of the Eocene has given rise locally to the topography characteristic of "Bad Lands."

**General considerations.** It has been customary to regard the Eocene and later periods as much shorter than those of the Paleo-


Fig. 473. Section showing the structure of the Eocene in western Oregon. *Eb*, Eocene basalt; *Ep* (Pulaski formation), and *Ec* (Coaledo formation), Eocene. Length of section about 20 miles. (Diller, Coos Bay, Ore., folio, U. S. Geol. Surv.)

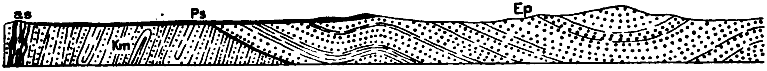



Fig. 474. Section a little south of the last, showing the relation of the Eocene (*Ep*, Pulaski formation) to the Cretaceous (*Km*, Myrtle formation). *as*, amphibolite schist, and *Ps*, Quaternary marine sand. (Coos Bay folio, U. S. Geol. Surv.)

zoic and Mesozoic; but this conclusion may be questioned. On the basis of thickness, the showing of the system is great, both on the Pacific coast, and in the western interior. Furthermore, any just estimate of the duration of the period must take account of the

[1] Lindgren and Drake, Nampa and Silver City, Idaho, folios, U. S. Geol. Surv., and Knowlton, Bull. 204, p. 110.

great erosion which followed the post-Cretaceous deformation. On the physical side, therefore, there is no warrant for assuming that the period was short. The faunal developments of the period were such as to make great demands upon time, and it is not improbable that the period was as long as the average of those of the Paleozoic and Mesozoic eras.

Such thicknesses of terrestrial sediment as occur in the Eocene of western North America, if they are really as great as reported. call for explanation. If the areas concerned were in process of more or less continuous warping, low areas going down as surrounding lands went up, or if troughs or basins of deposition were produced by faulting, the bottoms sinking while their surroundings rose, the conditions would perhaps be met.

The relations of the Eocene beds of the western interior indicate that both the attitude and altitude of the surfaces in that part of the continent were very different from those which now exist. That region must have been much lower than now, and, locally and temporarily at least, without well-established drainage. The present mountains were certainly not so high as now, though considerable elevations and great relief doubtless existed.

### *Close of the Period in North America*

The closing stages of the Eocene were marked by crustal movements in the west, resulting in considerable changes in geography. Some such movements had taken place during the period, as has been indicated; but the faulting and folding at its close were on a larger scale. The result was the retreat of the sea along the Pacific coast, the development of new areas of high and low lands, and therefore a shifting of the sites of rapid degradation and aggradation.

Along the Atlantic and Gulf coasts the Miocene is in many places unconformable on the Eocene, and it was at the close of the Eocene (or perhaps during the Oligocene) that an island, now included in the peninsula of Florida, was formed. In the Carolinas, and in the western Gulf region, the conformity between the Eocene and Oligocene formations seems to preclude notable changes of geography along the coast in the southeastern part of the United States at the close of the Eocene.

### *Foreign*

**Europe.** Considerable lakes, estuaries, and perhaps other areas of deposition remained over western Europe, at the close of

the Mesozoic era. Later, but still early in the Eocene, submergence set in, allowing the sea to cover considerable areas from which it had been excluded temporarily. In western and central Europe the maximum submergence of the Eocene seems to have been accomplished by the middle of the period. Toward its close, the epicontinental waters of the northwestern part of the continent were again restricted.

In the south, the Eocene sea spread much beyond the borders of the present Mediterranean, covering much of southern Europe and northern Africa. Eastward it joined the Indian Ocean, cutting off the southern peninsulas of Asia from the mainland to the north. A sound east of the Urals probably connected the Arctic Ocean with the expanded Mediterranean. Above this sea rose many islands, some of which corresponded in position to the Alps, Carpathians, Apennines, and Pyrenees.

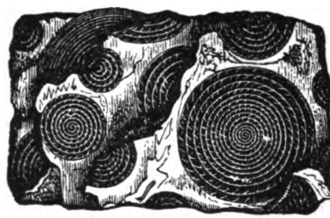


Fig. 475. A bit of nummulitic limestone.

On the bottom of this great body of water, limestone was deposited on an extensive scale. Much of it is made up almost wholly of the shells of nummulites (foraminifera, Fig. 475), and is found from one side of the Old World to the other. Since it is thick (locally several thousand feet) as well as widespread, the sea must have swarmed with foraminifera, and the period must have been long. In few other places are there indications of such great numbers of organisms of one kind. Some idea of the deformative movements since the Eocene may be gained from the fact that the nummulitic limestone occurs at elevations of more than 10,000 feet in the Alps, up to 16,000 feet in the Himalayas, and 20,000 feet in Tibet. In the Old World as well as in the New, the greater relief features of the present are post-Eocene.

**Other continents.** Marine Eocene is known along the northern and western coasts of *Africa*, and in the *Soudan*, in *South Australia*, *New Zealand*, and *Tasmania*, and in various islands of the Pacific. The Tertiary formations of *South America* have not been closely correlated with those of other continents. There is marine Eocene along some parts of the western coast, in Patagonia [1] (*Magellanian*

[1] Hatcher, Am. Jour. Sci., Vol. IV, 1897, p. 334, and Vol. IX, 1900, p. 97.

series) and probably elsewhere in Argentina, and along at least a part of the coast of Brazil.[1] Non-marine beds occur in Patagonia.

Eocene beds are extensive in the *West Indies* where limestone is the dominant rock. Formations of this age are said to occur up to elevations of 10,500 feet in Hayti.[2] It was formerly thought that the Atlantic and Pacific oceans connected freely somewhere south of the United States during the early Tertiary, but the work of Hill renders it doubtful whether there were more than shallow and restricted connections in the Eocene, and whether there was connection of any sort later.

### *General Geography of the Eocene*

The geography of the Eocene was very different from that of the present time, and the differences were perhaps even greater than has been indicated. It has been conjectured that North America was connected with Asia on the west, by way of Alaska, and with Europe on the east, by way of Greenland and Iceland. Land seems to have failed of making a circuit in the high latitudes of the north only by the strait or sound east of the Urals. In the southern hemisphere, it has been surmised that Antarctica was greatly extended, connecting with South America, Australia, and possibly with Africa, and that Africa and South America were connected across the Pacific from some earlier time until after the beginning of the Eocene. The basis for these conjectures is found in the distribution of life at that time, as shown by fossils.

If these conjectured extensions of land were real, it will be seen that the division of land and water in the northern and southern hemispheres was far less unequal than now, that the land was massed in high latitudes to a great extent, and that tropical seas were more extensive. If extensive polar lands were the cause of glacial periods, as some have thought, the geographic conditions of the Eocene were favorable in the extreme for glaciation, if the relations sketched above were the real ones. In spite of this, the climate of the period seems to have been genial, and less markedly zonal than now.

**Close of the Eocene.** During the later part of this period, and

[1] Branner, Bull. Geol. Soc. Am., Vol. XIII, and Stone Reefs of Brazil, Mus. of Comp. Zoöl., Bull. 44, pp. 27–53.

[2] Hill, Geological History of the Isthmus of Panama and Portions of Costa Rica. Bull. Mus. of Comp. Zoöl., Cambridge, 1898. Also J. P. Smith, Science, Vol. 30, 1909, p. 348.

at its close, there were some notable deformations in southern Europe. The initiation of the Pyrenees, and of some of the mountains farther east, are among the larger disturbances assigned to this time. The greater deformations which expressed themselves in the mountains of Southern Europe were post-Eocene, and most of them considerably later than the close of the Eocene.

## LIFE

**Transition from the Mesozoic.** Four salient features marked the transition of life from the Mesozoic to the Cenozoic: (1) among marine animals, nearly all Cretaceous species were replaced by new ones; (2) so many species of land plants lived on as to make it difficult to separate the Mesozoic from the Cenozoic; (3) the great saurians almost disappeared, and most other reptiles showed profound changes; and (4) mammals appeared in force, and promptly took a leading place.

The great change in the epicontinental marine life was due, no doubt, to the withdrawal of the sea from the continent, and the great restriction of the area of shallow water. The increase of the land and the establishment of new land connections may well have caused the existing vegetation to spread and flourish, if the climate remained congenial; but the land faunas did not respond in like manner.

It is an open question whether the Eocene mammals of North America and Eurasia descended from the primitive types of mammals which lived in these continents earlier, or whether they were immigrants. Satisfactory evidence of their descent from the early (non-placental) mammals is wanting, and the suddenness of their appearance in great numbers suggests invasion from some other quarter. The deformative movements which inaugurated the Eocene period quite certainly made new land connections, and furnished the conditions for an invasion, if mammals, developed elsewhere, were awaiting the opportunity.

Perhaps the rise of mammals caused the downfall of the reptiles. The habit of bringing forth relatively mature offspring, and of nourishing and protecting them, gave the mammals an immense advantage, to which were added superior agility and higher brain power. It would not be surprising, therefore, if the rise of mammals drove the clumsy, small-brained reptiles either to extinction, or to the assumption of new and smaller forms.

### *Vegetation*

In plant history the Eocene was not the dawn of the recent, for the change from medieval to modern plants took place in the Comanchean period. The Eocene did not even mark any radical innovation. There was, however, much progress toward living species, and toward present adaptations of plants to climate, soil, and topography, and to each other.

Among the plants of the earliest known Tertiary flora of Europe were oaks like those of the present high lands of warm temperate zones. With them were willows, chestnuts, laurels, etc., which have been likened to the flora of southern Japan. The flora of the Denver beds (p. 539), contains figs, poplars, laurels, magnolias, and many ferns. The early Eocene flora of southern Canada included similar forms, together with oaks, beeches, etc., a flora indicating a temperate climate.

The Middle Eocene of England records a flora "the most tropical in general aspect which has yet been studied in the northern hemisphere,"[1] while a later flora "suggests a comparison of its climate and forests with those of the Malay Archipelago and tropical America." The mid-Eocene of America in temperate latitudes contains palms and bananas, mingled with many other trees of similar climatic significance. The Eocene flora of Alaska indicates a climate comparable to that of Southern California and Florida. This flora shows a curious commingling of Jurassic and Cretaceous types (cycads), with angiosperms. A similar flora in the island of Saghalien indicates land connection between Alaska and Asia.[2]

### *Early Eocene Mammals*

The mammals of the earliest Eocene included several poorly differentiated groups, in which existing orders were foreshadowed rather than represented. The herbivores were foreshadowed by the *Condylarthra*, and the carnivores by the *Creodonta;* but the two groups were not sharply differentiated. Both were five-toed plantigrades, whose phalanges had horny coverings that were neither hoofs nor claws. *Edentates*, *insectivores*, *rodents*, and *lemuroids* seem to have been represented or foreshadowed. Evolution was so rapid that before the close of the Eocene, most existing groups of mammals were well defined (p. 686). None of the present *genera*, however,

[1] Geikie, Textbook of Geology, 3d ed., p. 974.
[2] Hollick, Am. Jour. Sci., Vol. 31, 1911, pp. 327–30.

existed then. In general, the mammalian faunas of the Eocene of North America were closely similar to those of western Europe, while during the Middle and Late Eocene there seems to have been faunal separation between these continents.[1]

**Main herbivore line.** While the condylarths and creodonts were near each other at the beginning of the period, the hoofed herbivores and the clawed carnivores developed from them soon became distinct. The condylarths (Fig. 476) were small generalized

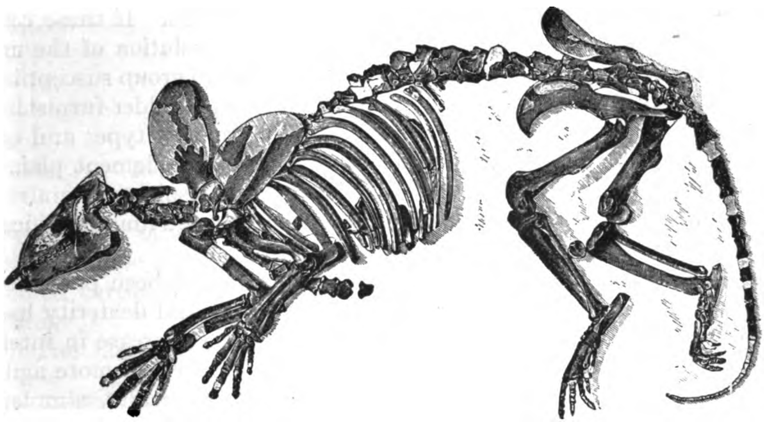


Fig. 476. A primitive ungulate or condylarth of the Wasatch epoch; *Phenacodus primævus* Cope, about 1/13 natural size (about the size of a tapir), from Big Horn basin, Wyoming. (Cope.)

forms with five toes and forty-four teeth, not yet developed into true herbivores. Condylarths did not live beyond the Eocene, but one branch adapted to forests and marshes seems to have diverged early, and perhaps to have given rise later to the ungulates. In the course of the period many of them became fitted for life on grassy plains. To this end, the flat, heavy, palmate form of foot adapted to marshes, gave place gradually to the light, springy, digitate form, adapted to a quick start and swift flight. At the same time hard hoofs, and grinding teeth were developed. The evolution of hoofs and grinding teeth has been thought to be connected with the prevalence of grassy plains, the firm turf of which is in contrast with the soft soil

[1] For references to important literature on the American Tertiary Mammalia, see the authors' larger work, Vol. III, p. 228. See also Osborn, Bull. 361, U. S. Geol. Surv., and The Age of Mammals; and Scott, A History of Land Mammals in the Western Hemisphere.

of forest and marsh. Forests perhaps helped to preserve a section of the evolving order in its more primitive form.

Back of these influences lay the physical conditions that promoted them. In western America, where the evolution is best known, the lakes and rivers were undergoing changes. As they shrank or shifted, they left behind them borders of grassy or sedgy ground which, on fuller drainage, may have become prairies. Such changes were suited to the evolution of herbivorous prairie life, and this in turn must have invited predaceous animals. If these considerations are valid, the prime factors in the evolution of the ungulates were (1) an undifferentiated plastic animal group susceptible of modification; (2) a plant group (grasses and fodder-furnishing angiosperms) affording appropriate food for the new type; and (3) the shrinkage and shifting of lakes, marshes, and lodgment plains, and the drying up of the plains of the continent, resulting in prairies whose hard turf favored the development of foot and limb modification in the interest of speed.

The era of bulk and heavy armor, such as had been possessed by the reptiles, had passed, and an era of agility and dexterity had begun. No small factor in this progress was the increase in intelligence indicated by the larger brains. The lighter and more agile frame was accompanied by the development of smaller, simpler, but more effective weapons of attack and defence. Nevertheless size continued to be important, and some species in almost every sub-order reached and passed the limit of bulk-advantage, and then declined.

In the course of the early evolution strange forms appeared, and soon became extinct. Among them were the *Dinocerata* (Fig. 477), grotesque monsters whose skulls were armed with three pairs of protuberances, perhaps horn cores, and a pair of enormous canine teeth or tusks projecting below (at least in the male), and an extravagant attempt at armature on both upper and nether sides. Their brains were singularly small for such ponderous bodies. In them, brute mass and low brain-power seem to have reached their climax among mammals.

**Divergence of ungulates into odd- and even-toed.** Early in the Eocene, hoofed animals began to diverge into odd-toed (*perissodactyls*) and even-toed (*artiodactyls*) types. In the former, the main line of support is in the axis of the middle toe; in the latter, between the third and fourth toes. In the course of time the lateral

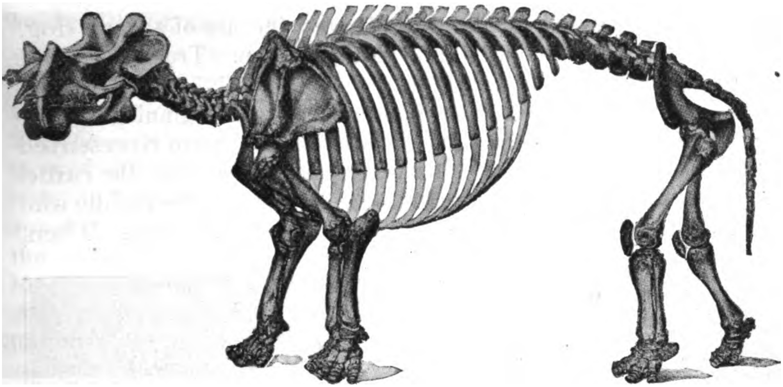


Fig. 477. *Dinoceras mirabile*, restoration of skeleton by Marsh; about 13 feet long. Middle Eocene, Wyoming.

toes fell out of use and were atrophied. The first class reached its extreme type at length in the horse, and the second in our cloven-hoofed cattle; but these perfected types were not attained in the Eocene.

The horse has become a classic example of evolution. The

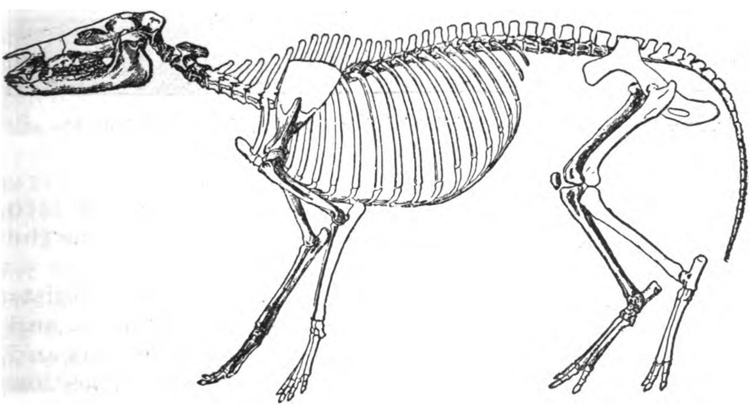


Fig. 478. An early ancestor of the horse family, *Hyracotherium* (*Protorohippus*) *venticolum*, from the Lower Eocene (Wind River formation) of Wyoming; about ¼ natural size. (Cope.)

earliest recognized form was the *Hyracotherium* (Fig. 478), which resembled the horse but little. The *Orohippus* (*Epihippus*) represented a greater advance. It was four-toed (three functional) in

front, and three-toed behind. It had about the size of a small dog, and was as much canine as equine in appearance. True horses did not appear till the Pliocene.

Artiodactyls emerged from their generalized beginnings more slowly. *Suina* (pigs, peccaries, hippopotamuses) were represented in the Bridger epoch by a small hog. Strangely enough, the camel family seems to have had its beginning in America in the middle and later Eocene, and to have flourished here until the Pliocene. Then,

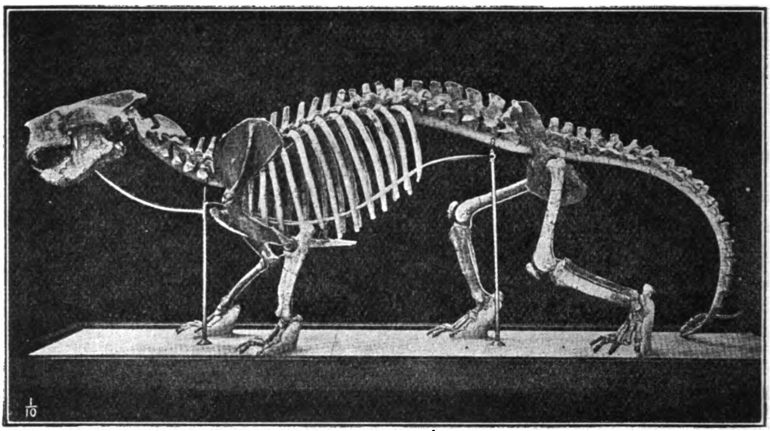


Fig. 479. Mounted skeleton of *Patriofelis*, a Creodont from the Middle Eocene of Wyoming; 1/18 natural size. (Osborn.)

having previously sent a branch to South America to evolve into llamas and vicunas, and another into the Old World to become the present camels, the tribe died out in its primitive home.

**Carnivore line.** It has been thought by some paleontologists that the *creodonts* were more primitive than the condylarths, and that the latter diverged from the former, as also the edentates and the rodents. If this is so, it gives the creodonts the central position among the primitive mammals. They lived throughout the period and into the next, gradually giving way to their own more progressive descendants. Toward the end of the period, modern types began to emerge definitely from the ancestral forms. Primitive representatives of the dog family appeared in Europe late in the period. Scott states that "clawed mammals long antedated the

hoofed types, and that the latter arose, either once or at several separate times, from the former.[1]

**Edentates, rodents, and insectivores.** The similarity of the ancestral *edentates* to the condylarths and creodonts of the earliest Eocene seems to imply that the three orders had but recently diverged from common ancestors. By the middle of the period, rodents became a notable element in the fauna. The squirrel appeared in Europe in the latter part of the period. Even to-day, the rodents retain many primitive characters, and since the Miocene have undergone few radical changes. Their derivation is not yet determined. Most living families of *insectivores* can be traced back to the Eocene. They still retain many primitive characters, and are the least altered of the great mammalian branches.

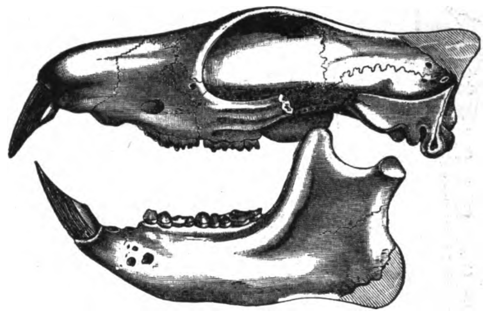


Fig. 480. The skull and jaw of a large Eocene rodent, *Tillotherium fodiens* Marsh, from the Bridger formation, Wyoming; about 1/6 natural size.

**Non-placental mammals.** During the period, opossums appeared in both hemispheres. They retained this wide distribution until the Miocene, when they disappeared from Europe, but they have persisted in North and South America to the present. It is a singular fact that the *monotremes*, the lowest of the mammals, are not known until after the Tertiary.

**The primates.** No traces of apes have been found in the Eocene, but lemuroids appeared in the Wasatch epoch in America, and in a similar horizon in Europe. This is the more notable, as the lemurs are now confined to Madagascar, Africa, and southern Asia. They have many affinities with the insectivores, and were possibly derived from them. Apes probably descended from the early lemuroids.

**Mammals go down to sea.** Some mammals took to the sea by choice or necessity, as land reptiles did before them. Thus arose *cetaceans* (whales, dolphins, porpoises), *sirenians* (manatees, dugongs), and *pinnipeds* (seals, sea-lions). In parts of Alabama, vertebræ of primitive whales (*Zeuglodons*) were originally so abundant

[1] A History of Land Mammals in the Western Hemisphere.

as to attract popular attention, and call forth legends of divers catastrophes.

**Birds.** Fossils of many types of birds, such as gulls, herons, eagles, owls, quails, plovers, and flightless birds of great size, show great deployment of this class.

**Reptiles and amphibians.** One of the greatest contrasts in geological history is found in comparing the size, power, and multitude of the Cretaceous land reptiles with those of the Eocene. Of the great saurians, only a few lived on into the early Eocene. Land reptiles seem to have become rare early in the period, though there

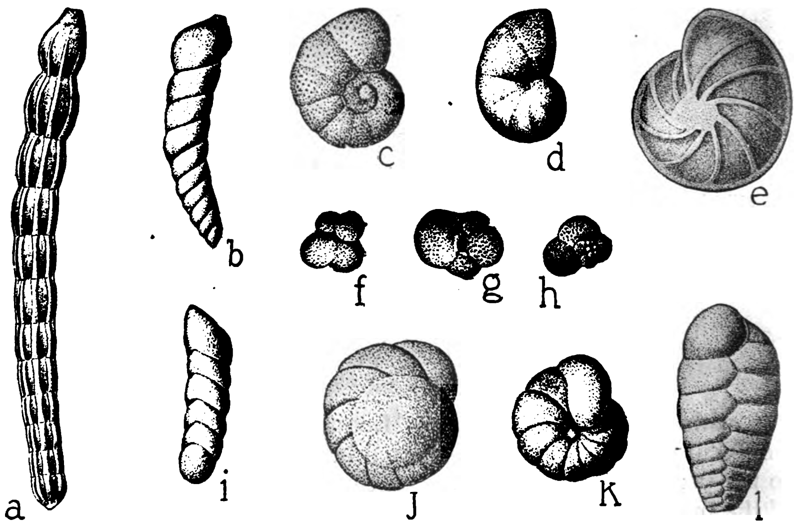



Fig. 481. Eocene Foraminifera. *a, Nodosaria bacillum* Defrance; *b, N. communis* (d'Orbigny); *c, Anomalina ammonoides* (Reuss); *d, Cristellaria gibba* d'Orbigny; *e, C. radiata* (Bornemann); *f, g,* and *h, Globigerina bulloides* d'Orbigny; *i, Vaginalina legumen* (Linné); *j, Discorbina turbo* (d'Orbigny); *k, Truncatulina lobatula* (Walker and Jacob); *l, Textularia subangulata* (d'Orbigny). Magnified 8 to 40 times. (Maryland Geol. Surv.)

were turtles on the land and in the sea, and some of them attained large size. There were crocodiles which belonged about equally to land and water; also snakes, some of them large. Amphibians were present, but apparently not abundant.

**Insect life.** There has been little important change in the insect world since the beginning of the Cenozoic. Few new families have appeared, though genera and species have changed.

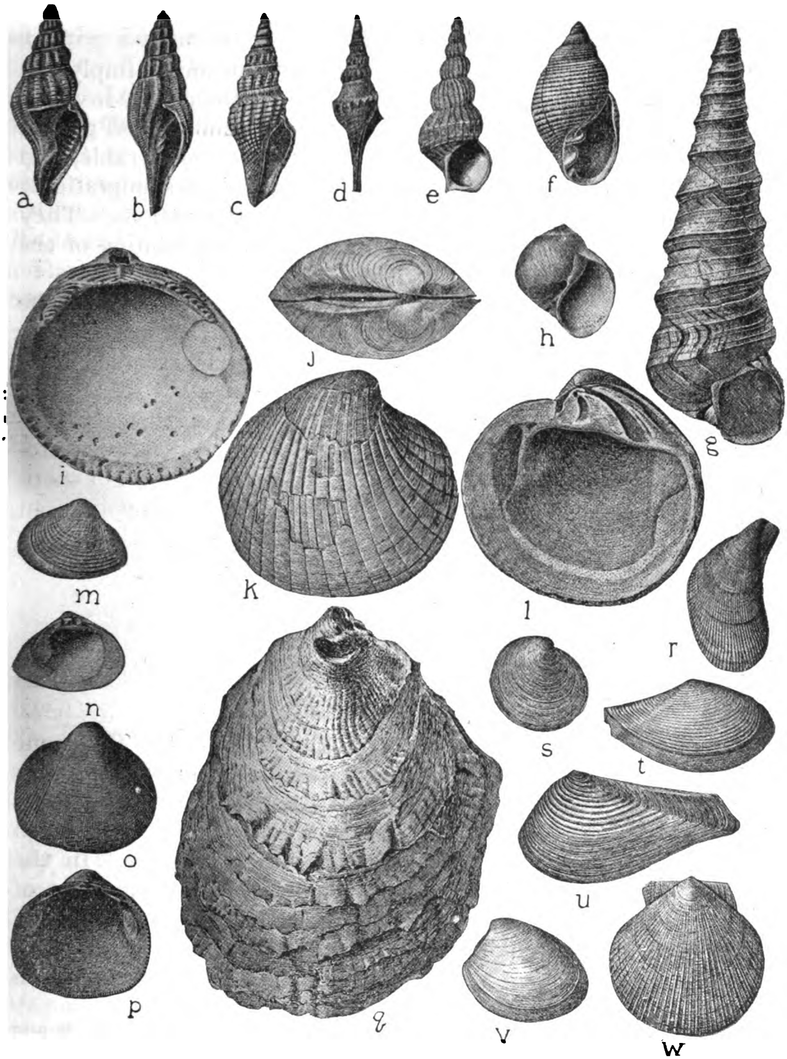



Fig. 482. Eocene Mollusks. *a-h*, Gastropods: *a*, *Fusus* (?) *interstriatus* Heilprin; *b*, *Mitra potomacensis* Clark and Martin; *c*, *Pleurotoma tysoni* Clark and Martin; *d*, *P. potomacensis* Clark and Martin; *e*, *Scala potomacensis* Clark and Martin; *f*, *Tornatellæa bella* Conrad; *g*, *Turritella mortoni Conrad; h*, *Lunatia marylandica* Conrad. *i-w*, Pelecypods: *i*, *Glycimeris idoneus* (Conrad); *j*, *Dosiniopis*

Continued at the bottom of p. 574.

### *Marine Life*

The name Eocene (dawn of the recent) was meant to imply the presence of less than 5% of *living* species among the marine invertebrates of the period; but most existing orders, families, and genera were established. The changes of later times are considerable, and are valuable as criteria for correlation, climatic changes, migrations, etc., but they are not profound biological transformations. They are in striking contrast with the radical and rapid evolution of the mammals.

Geologically, the most striking feature of the marine Eocene life was the extraordinary abundance and size of the *foraminifers* (Fig. 481). Most types of marine invertebrates had assumed their modern forms.

The American Eocene faunas were rather pronouncedly provincial, though some species have a rather wide range. So pronounced is their provincial character that much difficulty is experienced in making correlations between formations along different parts of the Atlantic and Gulf coasts, and greater difficulties arise in regions more widely separated. The variations are, however, variations of detail, not of broad features.

The marine fauna of the Pacific coast,[1] and the flora as far north as Puget Sound, indicate a subtropical climate.

## OLIGOCENE FORMATIONS

**North America.** Formations corresponding to the Oligocene of Europe have not been differentiated completely in North America;[2] but certain formations along the Atlantic and Gulf coasts, formerly classed as late Eocene or early Miocene, may be regarded as equivalent to some part of the Oligocene of Europe. In the Gulf region the Vicksburg (below) and Grand Gulf formations of Alabama, Mississippi, and Louisiana, and the Fayette formation of Texas, belong to this category. The early Oligocene is represented generously about the Caribbean sea, where its association

*lenticularis* (Rogers); *k* and *l*, *Venaricardia marylandica* Clark and Martin; *m* and *n*, *Corbula aldrichi* Meyer; *o* and *p*, *Protocardia levis* Conrad; *q*, *Ostrea compressirostra* Say; *r*, *Modiolus alabamensis* Aldrich; *s*, *Lucina aquiana* Clark; *t*, *Leda parilis* (Conrad); *u*, *Crassatellites alæformis* (Conrad); *v*, *Nucula ovula* Lea; *w*, *Pecten choctawensis* Aldrich. (Maryland Geol. Surv.)

[1] Arnold, Jour. Geol., Vol. XVII, p. 509, and Knowlton, Tacoma, Wash., Folio.
[2] Dall, 18th Ann. Rept., U. S. Geol. Surv., Pt. II.

with the Eocene is close,[1] and its separation from the Miocene distinct. This is in keeping with the phenomena of the Gulf States. Limestone is the dominant rock in the Antillean region.

The Oligocene stage is also recognized among the terrestrial deposits of the western part of the continent. The *White River* formation, now classed as Oligocene, occupies an extensive area in northeastern Colorado, southwestern Wyoming, western Nebraska (*Brule* and *Chadron* formations), and South Dakota, and perhaps in Kansas. In the light of present knowledge, it seems probable that all phases of land aggradation, lacustrine, fluvial, and eolian,

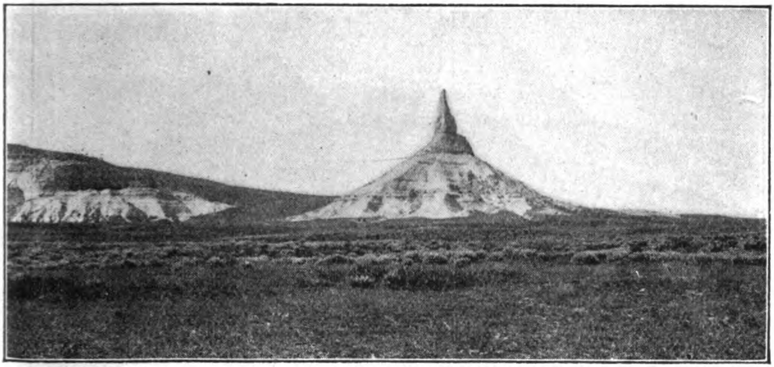


Fig. 483. Chimney Rock, a detail in the Bad Lands of the White River country. The base of the column is Brule clay. (Darton, U. S. Geol. Surv.)

are represented in this formation.[2] Even thin beds and lenses of limestone and volcanic ash enter into it. The formation is said originally to have covered most of the Black Hills region, and possibly all of it.[3] Remnants are found up to elevations of more than 6,000 feet, and the highest points of the hills are but little higher. The *Florissant* beds in South Park, Colorado, consisting largely of volcanic ash, and famous for their fossil insects, are classed as Oligocene. So also are some of the beds of the John Day Basin of Oregon, unconformable above the Eocene. Marine Oligocene beds

[1] Hill, Geology and Physical Geography of Jamaica, and Geological History of the Isthmus of Panama and portions of Costa Rica. Bull., Mus. Comp. Zoöl., Vols. XXVIII and XXXIV respectively.

[2] Fraas, Science, Vol. XIV, N. S., p. 212, and Matthew, Am. Nat., Vol. XXXIII, p. 403, 1899.

[3] Darton, 19th Ann. Rept., U. S. Geol. Surv., Pt. IV; 21st Ann. Rept., U. S. Geol. Surv., II.

are found on the Pacific coast, but the record of the period here is found chiefly in the unconformity between the Eocene and the Miocene.

Considerable geographic changes occurred during the Oligocene, or at its close, especially in the Gulf and Caribbean regions, where the Oligocene (early Oligocene) is commonly conformable on the Eocene, and unconformable beneath the Miocene.

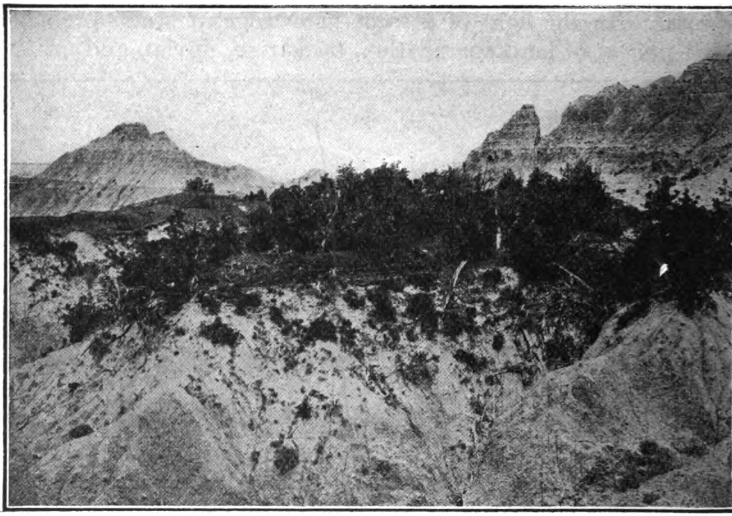


Fig. 484. Oligocene Bad Lands of South Dakota. (Williston.)

**Europe.** Toward the close of the Eocene, the epicontinental sea of northern Europe was greatly restricted, but considerable areas stood so near sea-level that slight changes served greatly to diminish or extend the epicontinental waters.

The oldest Oligocene deposits of central and western Europe are largely of terrestrial, fresh- and brackish-water origin. Local deposits of salt, gypsum, and coal are suggestive of the physical conditions at various times and places. The Oligocene of southern Europe is chiefly marine.

In Europe, as in North America, there were considerable igneous eruptions during the Tertiary, and especially during the Oligocene. Between eruptions, vegetation grew in marshes and shallow lakes

and over the surface of the lava. The substance of this vegetation is locally (Faroe Islands and Iceland) preserved in the form of coal between the lava beds.

*Amber*. One of the peculiar accessories in the Lower Oligocene is the amber of northern Germany, principally in the vicinity of Königsberg. While amber in small quantities is found in Sicily and a few other places, that of the Baltic region is more abundant than that of any other part of the earth, so far as now known. Amber is fossilized resin, apparently from certain varieties of coniferous trees. Its original position in the Baltic region appears to be in certain beds of a clayey nature, but parts of this formation have been worn by the waves, and the amber distributed. Some of that which finds its way into commerce is picked up on the Baltic shore, while some is taken from the beds in which it was originally entombed. One of the interesting features of the amber is the fact that it contains numerous insects. They seem to have alighted upon the resin while it was soft, and to have become completely immersed in it, and perfectly preserved. About 2,000 species have been found thus embedded.

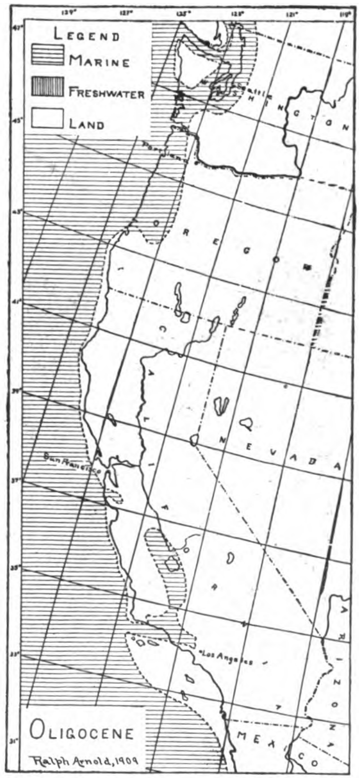



Fig. 485. Map showing supposed distribution of land and water on the Pacific coast of the United States during the Oligocene epoch. (Ralph Arnold.)

Considerable deformative movements made themselves felt in southern Europe at or about the close of the Oligocene, as in the Balkan and Carpathian Mountains.[1]

**Other continents.** In other continents, the Oligocene has not

[1] Willis. Carnegie Institution Year Book 4, 1905.

been generally differentiated, but it is known in northern Africa and in Patagonia,[1] where it is partly marine and partly non-marine.

### OLIGOCENE LIFE

**Vegetation.** The forests of the Oligocene were similar to those of the Eocene, especially in Europe, where palms continued to be abundant and varied, growing even in north Germany. The Florissant beds of Colorado contain a variety of angiosperms, representative of orders now found in the latitude of the middle and southern states.

**Land animals.** All species of *insects* in the Florissant beds (over 700) are extinct. This indicates that although the types had

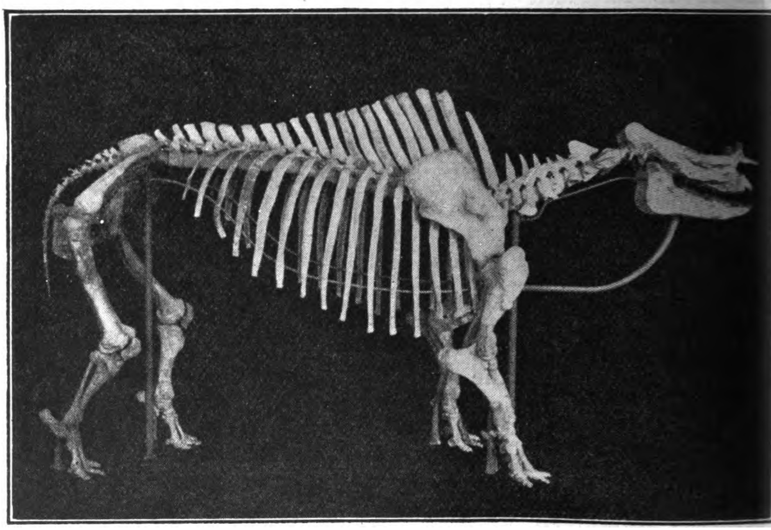


Fig. 486. *Titanotherium validum* Marsh, photograph of a mounted specimen in the Carnegie Museum. (Holland.)

become modern, the species continued to change with relative rapidity. Fish fossils are abundant in the same beds.

*Mammals* continued their rapid evolution. The *Carnivora* came into clear definition, and were represented in the White River beds by ancestral dogs, cats, raccoons, and weasels, while some creo-

[1] Hatcher, Geol. Mag., 1902, p. 136.

donts remained. Rodents were represented by squirrels, beavers, pocket-gophers, rabbits, and mice. Among perissodactyls, the rapidly developing horse family was represented by *Mesohippus* and *Anchippus*. The *rhinoceros* tribe had deployed into three branches, one a lowland form, ancestral to the existing family, one aquatic, and a third an upland running form. The tribe had a cosmopolitan range.

An erratic branch (the *titanotheres*) of the odd-toed ungulates which arose late in the Eocene reached its climax in the Oligo-

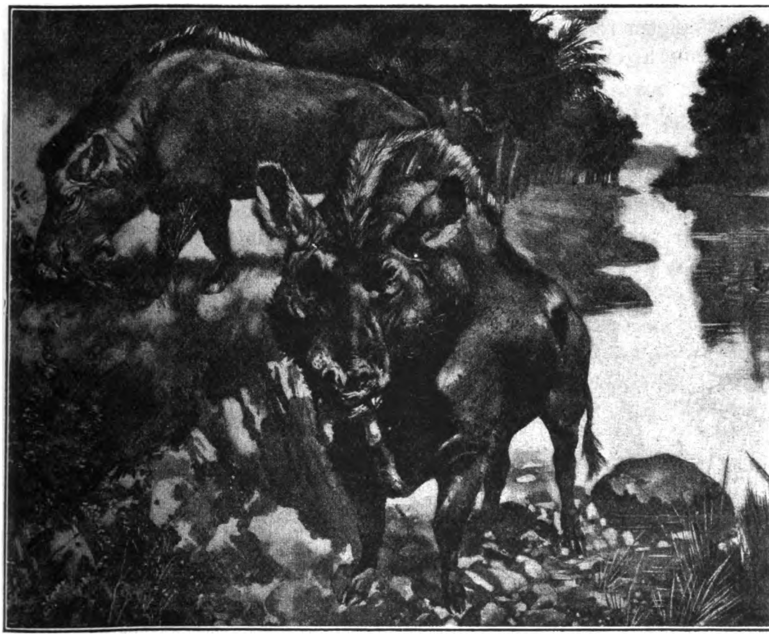


Fig. 487. An interpretation of the elotheres, or giant pigs, of the White River epoch, drawn by Charles R. Knight. (From drawing in American Museum of Natural History. Copyrighted by the Museum.)

cene (White River), and then disappeared. Its representatives were distinguished by a long, depressed skull, armed with a pair of horns near the end of the nose (Fig. 486). They reached some fourteen feet in length and ten in height. They were American and apparently rather local. Another odd type was the *elothere*, which

appeared in North America in the White River stage, and continued into the Miocene. An interpretation of their general appearance is shown in Fig. 487. Artiodactyls were prominent, represented by various extinct forms, and by ancestral peccaries, camels, ruminants, and other forms.

*Marine life.* The fauna of the Oligocene on the Atlantic coast of North America has the same general aspect as that of the Eocene. Later, however, provincialism became pronounced. By this time, the foraminifers had declined greatly, and the fauna was overwhelmingly molluscan. On the Pacific coast, the Oligocene fauna shows closer relation to the Miocene fauna than to the Eocene, and suggests a climate intermediate between the climates of those periods

# CHAPTER XXVII

## THE MIOCENE PERIOD[1]

### FORMATIONS AND PHYSICAL HISTORY

The geography of the North American continent during the Miocene period was similar to that of the Eocene. The slight emergence of the coastal borders after the Eocene (or early Oligocene) was followed by a slight submergence of the same regions during the Miocene. In the western interior, terrestrial aggradation of all phases continued, but the sites of principal deposition differed somewhat from those of the preceding period.

**The Atlantic coast.** In its surface distribution, the Miocene sustains the same relation to the Eocene that the latter does to the Cretaceous (Fig. 446), though in places the Miocene overlaps the Eocene, completely concealing it. There is generally a slight unconformity at the base of the Miocene. Like the other formations of the Coastal Plain, the beds dip seaward and are concealed by younger beds some distance to landward from the present shore. The system originally extended inland far beyond its present border, as shown by numerous outliers.

The Miocene of the Atlantic coast is composed chiefly of unconsolidated sand and clay. In places there is shell marl, and locally beds of diatomaceous earth of such thickness (30 or 40 feet) as to be valuable commercially. At the north, the Miocene has a thickness of 700 feet, but it thins southward. The Miocene of this coast is generally called the *Chesapeake* formation. It was formerly regarded as Upper Miocene, the former Lower Miocene being now classed as Oligocene. The fauna of the Chesapeake series has been interpreted to indicate a climate somewhat cooler than that which had preceded.

**The Gulf coast.** The Miocene of the Gulf coast is rather thin, and sustains the same general relations to older formations as that

[1] Dall and Harris, Bull. 84, U. S. Geol. Surv., and Dall, 18th Ann. Rept., U. S. Geol. Surv., Pt. II.

Fig. 488. Map showing the distribution of the Miocene formations in North America. Conventions as in preceding maps.

of the Atlantic, except that it is not known to be so generally unconformable on formations below. In Florida, Miocene limestone has

been changed locally to lime phosphate.[1] The alteration appears to have been effected through organic matter, especially the animal excrements accumulated about bird, seal, and perhaps other rookeries. The organic matter furnished the phosphoric acid, which, carried down in solution, changed the carbonate of lime to the phosphate. The phosphate is used extensively as a fertilizer. In Texas part of the Miocene is non-marine. Much of the oil of Texas and Louisiana comes from dolomized limestone which is probably Miocene.[2]

**The Pacific coast.**[3] At the beginning of the period, the sea encroached upon the Pacific coast, covering considerable areas which were land during the Oligocene. It flooded the southern part of the central valley of California early in the period, and later the northern part as well. At about the beginning of the period, faulting seems to have affected considerable parts of California, and some of the planes of movement at that time have served as planes of movement since. This was the time of the first definitely recognized movement along the great *earthquake rift* of California. Though subsidence was the rule in central and southern California, local fault-blocks seem to have had notable elevation.

The Miocene history of the Pacific coast is divided into two somewhat distinct epochs, separated by diastrophism and vulcanism. During the first epoch, besides clastic formations and volcanic ash, there is a formation (*Monterey*) containing much diatomaceous material which is an important source of oil.[4] The amount of siliceous material ascribed to diatoms is prodigious, and seems credible only when the extraordinary rate of reproduction of diatoms is recalled. It has been estimated that a million individuals might come from one, in the course of a month. If this is the fact, it is perhaps not strange that large amounts of siliceous material accumulated where conditions favored.

After the early Miocene there were extensive igneous eruptions in eastern Washington, Oregon, and the Coast ranges of California. South of San Francisco, this was the time of the last important

[1] Penrose, Bull. 46, U. S. Geol. Surv.
[2] Hayes, Bull. 213, U. S. Geol. Surv., p. 346.
[3] Arnold, Ralph, Jour. Geol., Vol. XVII.
[4] Eldridge, Bull. 213, U. S. Geol. Surv.; Arnold and Anderson, Bull. 322, U. S. Geol. Surv.,

eruptions in the Coast ranges, though farther north vulcanism continued later. The igneous eruptions were accompanied by diastrophism, which consisted in the readjustment of fault-blocks and folds throughout the Pacific coast region. Even high mountains were

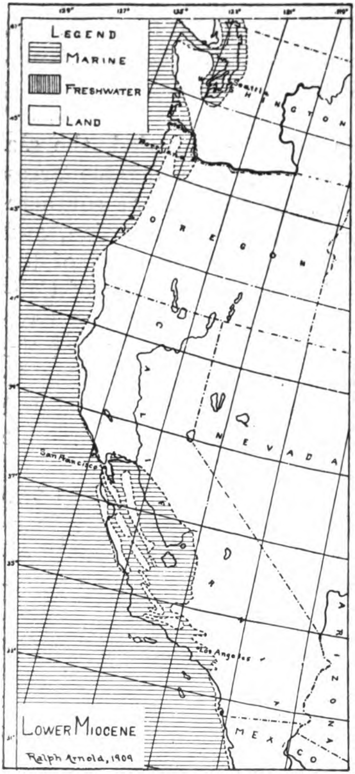



Fig. 489

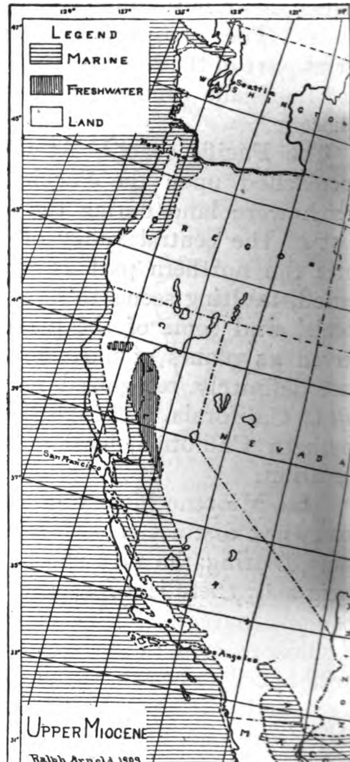



Fig. 490

Fig. 489. Map showing supposed distribution of land and water on the Pacific coast during the early Miocene period. (Ralph Arnold.)

Fig. 490. Map showing supposed distribution of land and water on the Pacific coast during the late Miocene period. (Ralph Arnold.)

developed locally, as shown by the coarseness of the sediments which followed.

The diastrophism resulted in the extension of the sea, for the Upper Miocene is more widespread than the lower. If a two-fold

division of the Tertiary were adopted, the earlier part of the Miocene should go with the early Tertiary, and the later part with the late Tertiary. The marine part of the system has great thickness, the Lower Miocene having a maximum thickness of some 8,000 feet, and the Upper hardly less.

By the end of the period, the peneplanation of the Klamath and Sierra Nevada Mountains seems to have approached completion.

Fig. 491. Contorted beds of Monterey shale. Mouth of Vaquero Creek, Cal. (Lippincott, U. S. Geol. Surv.)

Much of the material eroded from them had been deposited in the central valley of northern California, making the thick Miocene beds of that valley.

In western Oregon, Miocene (*Empire*) beds a few hundred feet thick, containing volcanic ash, rest unconformably on the deformed and eroded Eocene. In British Columbia, there are both clastic and volcanic rocks referred to this period.

The Miocene of the western coast has not the simple structure of the corresponding beds along the Atlantic and Gulf coasts. The strata have been deformed so as to stand at high angles (Fig. 491) in many places, and locally (Mount Diablo range) they have

been folded, and the folds overturned so that Cretaceous and Eocene formations overlie the Miocene.

**Non-marine deposits.** In the northern part of the central valley of California there are deposits of estuarine, lacustrine, and probably subaërial origin (*Ione* formation) partly contemporaneous with the early Miocene marine beds farther south. They consist of the common sorts of clastic sediments, with some coal, iron, etc.

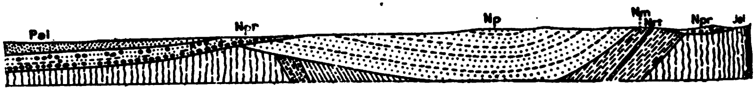



Fig. 492. Section showing the structure and relations of the Miocene system in the San Luis Obispo region of southern California. *Jsl*, San Luis formation, Jurassic; *Nm*, Monterey shale, Miocene; *Nrt*, rhyolite tuff; *Np*, Pismo formation, Miocene (?); *Npr*, Paso Robles formation, Pliocene; *Pal*, recent alluvium, etc.

Along the east side of this valley, auriferous gravels,[1] brought down by streams from the Sierras, were being deposited during at least a part of the period. These gravels seem to have been laid down on a surface of slight relief, interpreted as a peneplain.[2] The Sierra Mountains are thought to have been at least 4,000 feet lower than now when these gravels were deposited.

Non-marine Miocene beds are rather widespread in southeastern California and Oregon, reaching great thicknesses at some points in the vicinity of the 40th parallel. They include clastic sediments, volcanic debris, infusorial earths, and fresh-water limestones.

Farther east, on the western part of the Great Plains, the deposition of the *White River* beds may have continued for a time after the beginning of the Miocene. Late in the period, aggradation seems to have been renewed in the same general area, and the *Loup Fork* formation, thin but extensive, was spread over great areas from South Dakota to Mexico. The lacustrine phases of this formation are probably less extensive than the subaërial.[3] Like the White River formation, the Loup Fork beds have been eroded into "badland" topography (Figs. 68 and 69).

[1] Turner, 14th Ann. Rept., U. S. Geol. Surv., 1894; Lindgren, Jour. Geol. Vol. IV, 1896, pp. 881–906; Diller, Jour. Geol., Vol. II, pp. 32–54. See also folios of the Gold Belt of Calif., U. S. Geol. Surv.

[2] Diller, Jour. Geol., Vol. II, pp. 33–54.

[3] Haworth, Univ. Geol. Surv. of Kan., Vol. II, p. 281.

Non-marine deposits, largely of volcanic material, occur in British Columbia between the Coast and Gold ranges. Miocene deposits are known in Alaska, but erosion rather than deposition was the dominant process there, so far as present data show.

**Igneous activity during the Miocene.** The widespread igneous activity which began with the close of the Cretaceous, perhaps reached its climax during the Miocene. Igneous materials abound in the sedimentary formations of the system throughout the west, and igneous activity affected nearly or quite every state west of the Rocky Mountains, the eruptions being from fissures as well as volcanoes. Among the conspicuous centers of activity the basin of the Columbia and the Yellowstone National Park may be mentioned. Locally, forests were buried by the volcanic ejecta, and in favorable situations their trunks were petrified (Fig. 495). The lavas of at least a considerable part of 200,000 or 300,000 square miles of lava-covered country in the western part of the United States issued during this period, or during the time of crustal deformation which brought it to a close. Volcanoes were active in the Antillean region of Central America and the West Indies, and the Andean system of South America, as well as in North America.

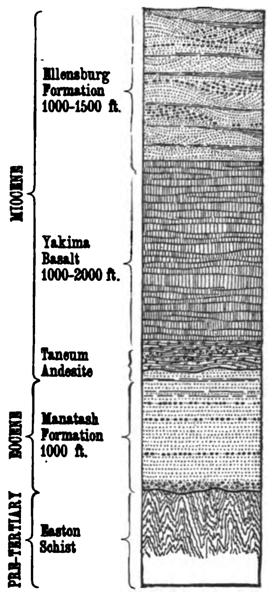



Fig. 493. Columnar section showing the succession of formations in central Washington. (G. O. Smith, U. S. Geol. Surv.)

**Close of the Miocene.** Slow warpings of the surface seem to have been in progress throughout the Cordilleran region during the Miocene period, accompanied by faulting and vulcanism, and locally, by pronounced orogenic movements; but toward the close of the period movements were more general. Pronounced deformation affected the coastal regions of Oregon and northern California, tilting and folding the Miocene and older formations. The principal folding of the existing Coast Ranges of both these states has been assigned to this time, but it now appears that some of the deformations formerly referred to the end of the Miocene took

place earlier (p. 583). The Cascade Mountains of Washington were in process of growth at this time.[1]

Similar movements were widespread east of the coast, as in the Great Basin region and elsewhere. In some places, they deformed strata heretofore horizontal, but more commonly they affected formations and areas which had suffered deformation earlier.

The later part of the period was perhaps the time when the greater relief features of the rugged west, as they now exist, were

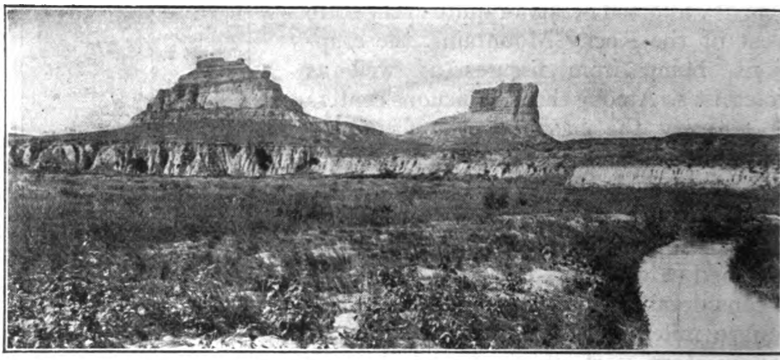


Fig. 494. Courthouse and Jail Rocks. Buttes of the Arikaree (Miocene) formation of western Nebraska. (Darton, U. S. Geol. Surv.)

initiated. The great relief features of earlier times appear to have lost their greatness before this time. After the movements of the late Miocene had been accomplished, it is probable that the western part of the continent had a topography comparable, in its relief, to that of the present, though by no means in close correspondence with it. The details, and many of the larger features, of the present topography are of still later origin.

In the eastern part of the continent, the geographic changes were less, though the Atlantic and Gulf regions seem to have emerged, shifting the coast-line to some such position as it has today.

*Foreign*

**Europe.** As compared with the Eocene, the sea on this continent was somewhat restricted in the north, and somewhat extended

[1] Willis, Professional Paper 19, U. S. Geol. Surv.

in the south. As in most other post-Paleozoic systems, non-marine formations have much representation in this. The marine beds are

Fig. 495. Petrified tree-trunks, Yellowstone National Park. (Iddings, U. S. Geol. Surv.)

chiefly along the Atlantic and Mediterranean. In the north, much of the system is buried beneath glacial drift. Thick conglomerates (3,900–5,900 feet) of early and middle Miocene age are found

along the north base of the Alps, and tell something of the relief of the Alpine region at the time. Southern Europe appears to have been an extensive archipelago, the plateau of Spain, parts of the Pyrenees, the Alps, and the Carpathian Mountains, and portions of adjacent lands being islands. The sea of southern Europe extended east far beyond the limits of the present Mediterranean, but late in the period it was much restricted.

The Miocene formations include all the common sorts of sedimentary rocks common to marine and non-marine deposits. The latter include not a little limestone of fresh-water origin, made partly from the secretions of algæ. In Italy the system is said to have a thickness of nearly 6,000 feet.

Considerable disturbances occurred in the later part of the period, and at its close. Before its end, the Alps had had a period of growth, usually placed at the close of the Lower Miocene. The Apennines and other mountains of southern Europe also were in process of development during the later Miocene. In the Caucasus Mountains, Miocene beds occur up to heights of 2,000 meters. As in America, widespread movements which were not notably deformative attended the growth of the mountains, with the result that the sea which had overspread southern Europe was greatly restricted, though not reduced to its present size. Igneous activity appears to have attended the movements, but not on such a scale as in North America.

**Other continents.** The Miocene of *Asia* has not been generally separated from the other Tertiary formations, but is known to be widely distributed in the southern part of the continent. In *Africa*, Miocene formations occur in Algeria and Lower Egypt, and are well represented in *Australia* and *New Zealand*. The beds are found up to heights of 4,000 feet, giving some clue to the extent of post-Miocene crustal deformation here.

In *South America*, Miocene beds probably occur on the western coast, and are known to have extensive development on the eastern plains of the southern part of the continent,[1] where the distinction between Upper Oligocene and Miocene is not sharp. The lower part of the Oligocene-Miocene series (*Patagonian* beds) is marine, while the upper part (*Santa Cruz*) is of fresh-water origin. The terrestrial

[1] Hatcher, Sedimentary Rocks of Southern Patagonia, Am. Jour. of Science, Vol. IX, 1900; and Ortmann, Princeton Univ. Repts. of Expedition to Patagonia, Vol. IV, Pt. II.

faunas of this region are strikingly similar to the Miocene and later faunas of Australia and New Zealand.

**Arctic latitudes and climate.** Miocene beds are somewhat widely distributed in the Arctic regions and seem to be largely of terrestrial origin, with fossil floras indicating a warm temperate climate.

## LIFE

### *Land Plants*

The mid-latitude flora of the Miocene records the gradual disappearance of subtropical types, and an increase of deciduous trees. This is particularly true of North America, where the flora came to resemble that of to-day in somewhat lower latitudes, and is indeed its predecessor. An important feature in North America was an increase in the grasses, with its appropriate effect on mammals.

### *Land Animals*

**Earlier fauna.** The early Miocene land fauna of North America was very distinct from the late Miocene. The former resembled

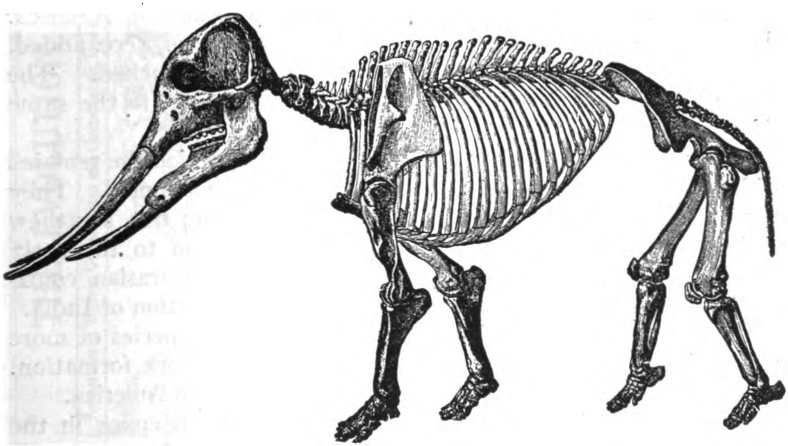


Fig. 496. A Miocene Mastodon, *Tetrabelodon angustidens* Cuvier. (Restoration by Gaudry.)

the Oligocene (White River) fauna. True carnivores, chiefly of the cat and dog families, had succeeded the primitive forms. Several branches of the perissodactyls had disappeared, reducing them

essentially to their three persistent lines, exemplified by the horse, the tapir, and the lowland rhinoceros. The even-toed branch also had developed into modern lines. Rodents were abundant, including squirrels, beavers, gophers, rabbits, etc.

**Later fauna.** *Elephants.* A notable addition to the mammalian fauna of North America in the late Miocene, was the *proboscidians.* Primitive proboscidians lived in Egypt at least as early as the Middle Eocene, and in Europe in the early Miocene. Elephants reached North America in the late Miocene, and South America in the Pliocene.

Much more important was the immigration of the modern *ruminants.* The great ruminant group that later formed so important a part of the fauna does not seem to have descended from early North American forms, but to have come in from Eurasia. Their remains are found in the Loup Fork beds. The first immigrants belonged to the deer and ox families. The earliest known deer (excluding *Protoceras*) were in Europe. They were hornless, as are their surviving relatives in Asia. By the middle of the Miocene, some of the males had acquired small two-pronged deciduous antlers. It was at this stage that they appeared in America. About the close of the period, three or four prongs were added, and in the Pliocene the antlers were variously branched. The Miocene skeletons imply lightness and speed, but not to the same degree as now.

There is some doubt as to the precise stage to which the remains of bison found in Nebraska and Kansas are to be assigned. They usually have been referred to the Lower Pliocene; but Matthew assigns them to the Upper Miocene, and Williston to the early Pleistocene. The earliest known bisons on the Eurasian continent were found in the Siwalik Lower Pliocene formation of India.

The earlier genera of camels were gone, but 15 species of more modern type have been identified from the Loup Fork formation. The family seems to have been confined still to North America.

*Evolution of the horse.* The Miocene was a great epoch in the evolution of the horse; *Anchippus*, *Protohippus*, *Pliohippus* (*Merychippus*), *Hipparion*, and other genera flourished, and forty or more species. They were still three-toed, but the two lateral toes were dwarfed and did not usually touch the ground, while the central one was strengthened and bore all the weight. A large group of structural features were being modified concurrently with the feet, to fit

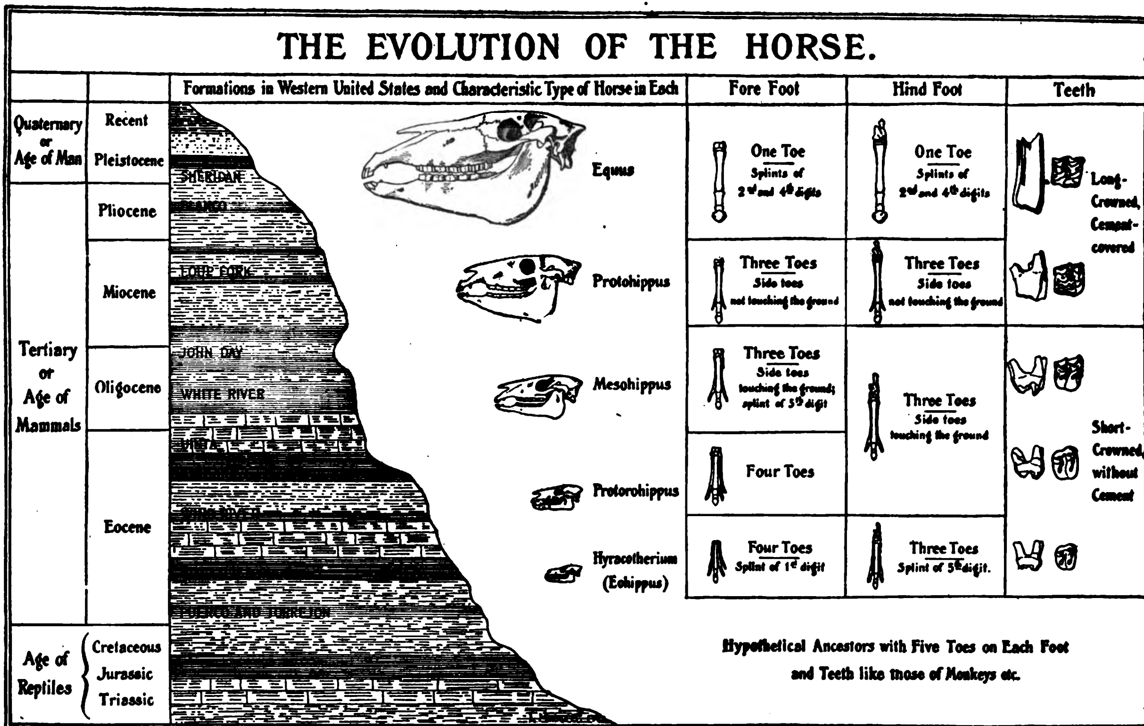



Fig. 497. The evolution of the horse. (After William D. Matthews, Am. Mus. Jour.)

the evolving horse to dry plains and grassy food (Fig. 497). The elimination of the side toes, the lengthening of the limbs, the concentration of the limb muscles near the body to reduce the weight of the parts most moved, and the consolidation of the leg bones, were modifications in the interest of speed and strength. An elongation of head and neck was necessary to reach the ground. The front teeth were reduced to chisel-like, cropping forms, while the molars, by developing ridges, became suited to grinding. The teeth also grew in length to provide for the great wear caused by the dry siliceous grasses.[1] It is probably as safe to infer a development of dry, grassy plains from this evolution of the horse as to infer climatic and topographic conditions from plants and other organic adaptations.

*Other orders.* Tapirs were but meagerly represented, but rhinoceroses were prominent. Most of the American species were hornless, but two-horned species appeared during the period in Europe. *Carnivores* were abundant, and had assumed forms referred with some doubt to the living genera. The dog family included numerous wolves and foxes; the cat family, panther-like animals and saber-toothed cats; weasel-like and otter-like forms, and an ancestral raccoon represented another family. The genera of the late Miocene were nearly all different from those of the early Miocene, indicating rapid evolution. *Rodents* were abundant, but neither insectivores nor primates are among the North American fossils. The development of the plains, which favored horses, deer, and cattle, was obviously unfavorable to the lemuroids.

*Primates.* In the Old World, apes had appeared. One type was rather large, combining some of the characters of apes and monkeys; another was related to the chimpanzee and gorilla, and about as large as the former. It is the view of some paleontologists that the ancestral branch of the *Hominidæ* (man) must have diverged from its relatives at least as early as this; but on the origin of man the geologic record throws no direct light.

*Lower vertebrates.* Little of moment is recorded relative to the lower vertebrates. Not much is known of American Miocene birds, but their advancement in later stages implies that they continued their evolution with measurable rapidity, a conclusion supported by the European evidence. Reptiles were represented by turtles, snakes, and crocodiles. Amphibians came again to notice in the

[1] For a recent illustrated statement of the evolution of the horse, see Matthew, Supplement to Am. Mus. Jour., Vol. III.

form of a large salamander, whose remains, found at Oeningen, Switzerland, formerly attained an unworthy celebrity from false identification as a human skeleton, and from the application of the pretentious name *Homo diluvii testis*.

**Summary**. A general view of the American Miocene land fauna shows that the great order of ungulates took precedence in evolution, and that both the odd- and even-toed branches participated actively. Closely following these in importance, and dependent on them for the conditions of their evolution, came the carnivores. Rodents occupied a middle position, and insectivores and lemuroids declined notably.

The European record bears a similar general interpretation, with the ungulates somewhat less pronouncedly in the lead, the carnivores somewhat better deployed, and the proboscidians a conspicuous factor. The important evolution of the higher primates seems to have been confined to the Old World.

### *Marine Life*

**Provincialism dominant.** The pronounced provincialism that had been inaugurated in the Oligocene epoch continued throughout the remainder of the Cenozoic era, being favored by the shallow seas about North America, and the bays and straits of Europe. Even the narrow border tracts that were geographically continuous show signs of having been cut into biological sections by interrupting barriers. The land being extensive, large rivers reached the coast here and there, and poured great volumes of fresh and muddy waters across the shore belt, doubtless forming barriers to some species. The warpings of the crust probably developed submarine ridges on the continental shelf. These were not only barriers in themselves, but had an influence in directing the courses of the coast currents. Differences of climate in different latitudes had been developed, apparently, and cold and warm currents were probably more pronounced than in earlier times, and their shiftings had still graver effects upon the faunas. So, too, the lower temperatures in the northern shore tracts of the Atlantic and Pacific prevented their serving longer as migratory routes for warm-water species, and this tended further to intensify the provincial nature of the shallow-water faunas.

According to Dall, the Chesapeake Miocene was ushered in by a marked faunal change due to a cold northern current driving out

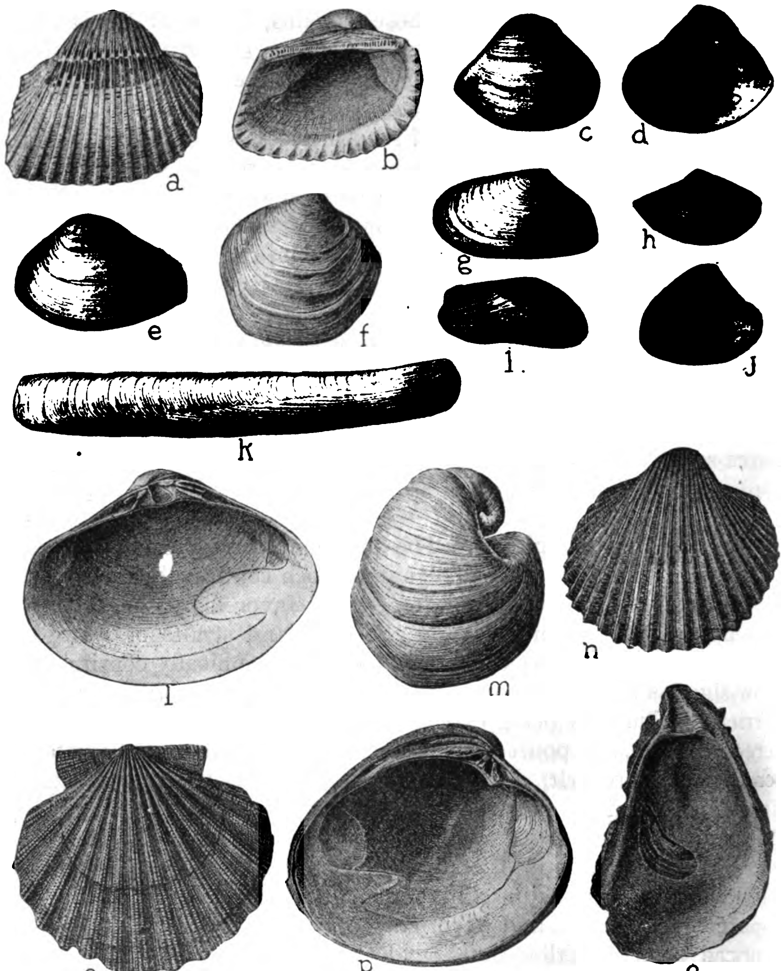



Fig. 498. Miocene Pelecypods: *a* and *b*, *Arca* (*Scapharca*) *staminea* Say; *c* and *d*, *Corbula idonea* Conrad; *e*, *Crassatellites marylandicus* (Conrad); *f*, *Phacoides* (*Pseudomiltha*) *foremani* (Conrad); *g*, *Tellina* (*Angulus*) *producta* Conrad; *h*, *Leda concentrica* (Say); *i*, *Modiolus dalli* Glenn; *j*, *Astarte thomasii* Conrad; *k*, *Ensis directus* (Conrad); *l*, *Spisula* (*Hemimactra*) *marylandica* Dall; *m*, *Isocardia markoëi* Conrad; *n*, *Cardium* (*Cerastoderma*) *leptopleurum* Conrad; *o*, *Pecten* (*Chlamys*) *madisonius* Say; *p*, *Venus ducatelli* Conrad; *q*, *Ostrea carolinensis* Conrad. (Maryland Geol. Surv.)

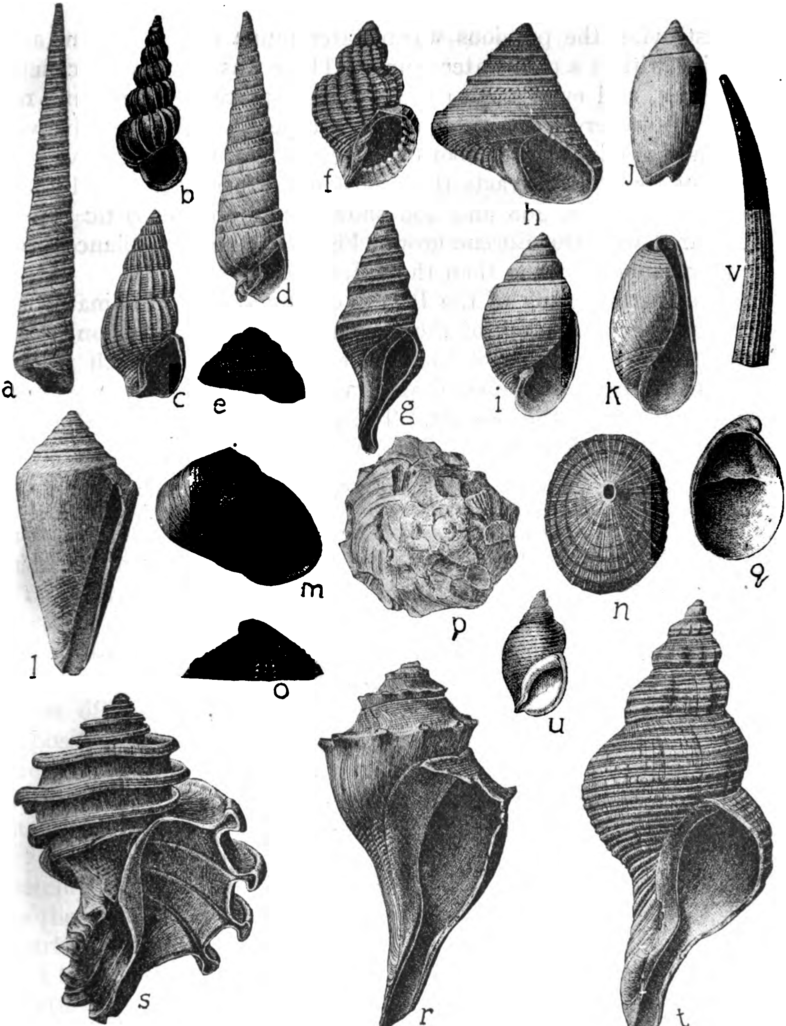



Fig. 499. Miocene Gastropods (one Scaphopod): *a*, *Turritella variabilis* Conrad; *b*, *Scala sayana* Dall; *c*, *Nassa marylandica* Martin; *d*, *Terebra unilineata* Conrad; *e*, *Solarium trilineatum* Conrad; *f*, *Cancellaria alternata* Conrad; *g*, *Surcula biscatenaria* Conrad; *h*. *Calliostoma philanthropus* (Conrad); *i*, *Actæon shilohensis* Whitfield; *j*, *Oliva litterata* Lamarck; *k*, *Retusa* (*Cylichnina*) *conulus* (Deshayes); *l*, *Conus diluvianus* Green; *m*, *Polynices* (*Neverita*) *duplicatus* (Say); *n*, *Fissuridea*

Continued on next page.

or destroying the previous warm-water fauna of the region, and bringing with it a cold-water fauna. There was a complete change of species, and even some genera were displaced. The fauna retained, however, a general molluscan aspect. Both the bivalves and the univalves gave proof of better adaptability to the vicissitudes of the coastal tracts than most other forms, and held their dominance. Figs. 498 and 499 show a few characteristic types. Compared with the Eocene group, Fig. 482, the resemblances will be found more striking than the differences.

The marine fauna of the Pacific coast indicates a climate but little warmer than that of the present, and this conclusion is reenforced by the plants of the Puget Sound region, which record a transition from the subtropical climate of the Eocene to the temperate climate of the present. The fauna of the Upper Miocene indicates a still closer approach to the present.

*alticosta* (Conrad); *o*, *F. griscomi* (Conrad); *p*, *Xenophora conchyliophora* (Born); *q*, *Crepidula fornicata* (Linné); *r*, *Fulgar spiniger* (Conrad) var.; *s*, *Ecphora quadricostata* (Say); *t*, *Siphonalia marylandica* Martin; *u*, *Ilyanassa* (?) (*Paranassa*) *porcina* (Say). Scaphopod: *v*, *Dentalium attenuatum* Say. (Maryland Geol. Surv.)

# CHAPTER XXVIII

## THE PLIOCENE PERIOD

### FORMATIONS AND PHYSICAL HISTORY

#### *Subaërial Formations*

The most distinguishing feature of the Pliocene formations, so far as the present continents are concerned, is the predominance of terrestrial deposits. This is a consequence of (1) the exceptional deformations which took place during the period, and before its beginning, and (2) the recency of the period, which has saved its deposits, to a large extent, from removal. Similar deposits after earlier periods of comparable deformation have been largely removed by later erosion. These deposits of the Pliocene are perhaps most obvious in intermontane regions such as the Great Basin. They have by some been interpreted as lacustrine deposits, and such no doubt exist; but over areas much greater than those occupied by Pliocene lakes, and over tracts which were never parts of well-defined flood plains, broad aprons of detritus accumulated. Most of the western mountains of America are flanked by such deposits of Pliocene age, or younger. Pliocene deposits of this type are doubtless concealed beneath later accumulations of a similar sort in nearly all the large basins, and at the bases of nearly all the steep slopes in the western mountain region.

In the Mississippi basin, far from all mountains, there are patches of gravel on various hills and ridges which are interpreted as the remnants of a once more or less continuous mantle of river detritus. Definite correlation of these gravels is not now possible, and they may not all be of the same age. They are not older than Cretaceous, and are older than the glacial drift. Their similarity to the Pliocene gravels farther south suggests their correlation with that formation. The material of these gravels, almost wholly quartz, quartzite, and chert, is partly local, and partly from the north. The leading topographic features of the Mississippi basin

have been developed since their deposition, for their remnants are on the highest lands within the area where they occur.

**The Lafayette formation.**[1] About the Atlantic and Gulf coasts similar deposition gave rise to the *Lafayette* (Orange Sand) formation, which seems to have had a history somewhat like that of the Pliocene beds of the west, though this interpretation has been challenged. This formation has an extensive distribution (1) between the Piedmont plateau and the Atlantic, (2) on the inland part of the Coastal Plain of the Gulf of Mexico, and (3) in the southern part of the Mississippi basin, and is represented, if our interpretation is correct, (4) in some of the valleys of the Appalachians and west of them. On the Coastal Plain of Texas the formation is connected with analogous deposits on the Great Plains, and through them with the intermontane deposits of the west, already mentioned. The term Lafayette has been applied only to the formation on the slope between the Appalachians and the Atlantic, about the Gulf, and in the Mississippi basin below the Ohio, where it lies upon the eroded edges of older formations, and extends inland from the coast up to altitudes of 1,000 feet[2] near the Rio Grande, 800 feet in Tennessee, and 300 to 500 feet on the Atlantic slope. At its mountainward edge, ragged belts of the Lafayette formation follow the valleys up into the mountains. At its seaward margin, it is more or less completely concealed by younger beds, and it is not to be doubted that it passes out to sea beneath them. No part of the formation on land is demonstrably marine.

Within the general area of its distribution the formation is not continuous. Over considerable areas, it caps divides, but is absent from the valleys between them, obviously the result of stream erosion. The base on which the formation rests has but little relief, and a gentle dip seaward.

In general, the formation thickens seaward. Its known thickness ranges from 0 to 200 feet or more, sections of 20 or 30 feet being common.

[1] The fullest sketch of this formation as a whole is that of McGee in the Twelfth Annual Report of the U. S. Geological Survey. A few references to other accounts of the formation in special localities, some of them under other names, are as follows: Safford, Am. Jour. Sci., Vol. XXXVII, 1864; Hilgard, Agric. and Geol. of Miss., 1860, and Am. Jour. Sci., Vol. XLI, 1866, and Vol. IV, 1872; Salisbury, Geol. Surv. of Ark., Report on Crowley's Ridge, 1889; Dumble, Jour. Geol., Vol. II, 1894, p. 560; Smith, E. A., and Johnson, L. C., Geol. Surv. of Ala., 1894.

[2] McGee, loc. cit.

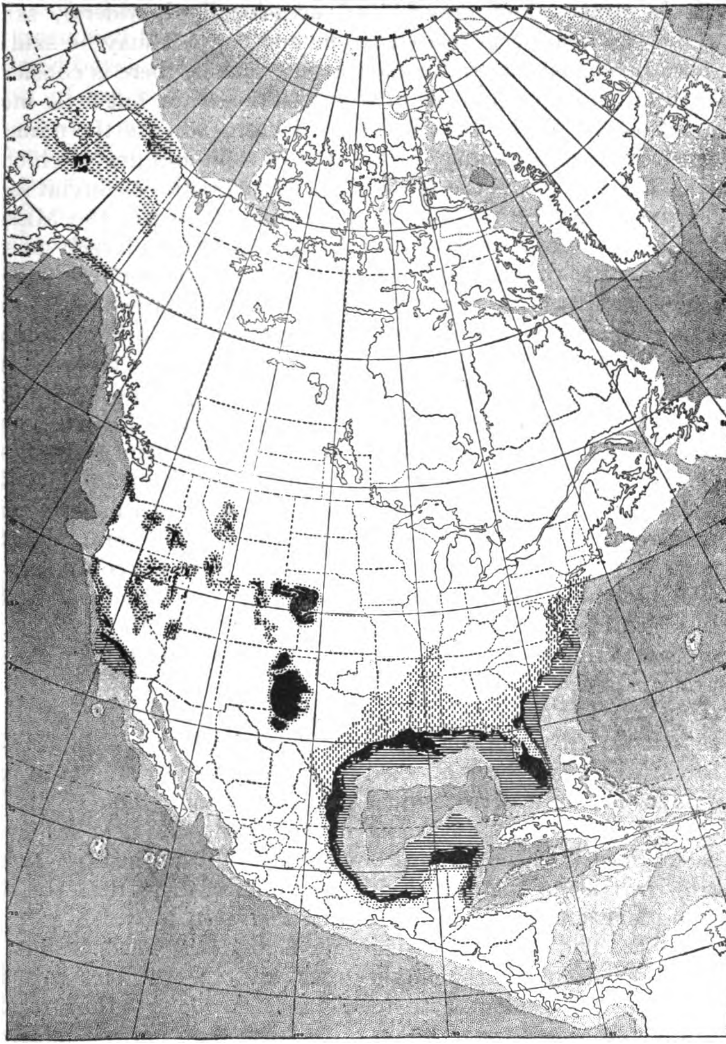


Fig. 500. Map showing the distribution of the better-known parts of the Pliocene system. The area of the Lafayette, along the Atlantic and Gulf coasts, is marked by vertical dashes. This formation doubtless is more widespread than the map shows. Relatively little of the exposed Pliocene is marine.

It is composed of gravel (and occasionally bowlders), sand, silt, and clay, variously related to one another. It may be said to be both heterogeneous and homogeneous; that is, there is considerable variation in composition in short distances, and but little more in great ones. In the lower Mississippi basin, whence the name is derived (Lafayette County, Miss.) it is of sand and gravel chiefly, having in many places the distinctive characteristics of fluvial sand and gravel. Over a broad tract of the uplands east of the Mississippi and away from valleys generally, it is composed largely of silt and clay. Its constituents are chiefly the insoluble residues of older formations farther up the continental slope on which it lies, chert and quartz pebbles making up its gravels, and other insoluble matter its fine constituents. These constituents replace one another at short intervals and in various ways, and no systematic succession is observable. Irregular stratification is the rule, but some portions are not bedded. Certain lenses of sand suggest an eolian origin, and pebbly-earths that find their analogue in subaërial and flood-plain deposits are common. The color of the formation ranges from brick-red through various pinks, purples, oranges, and yellows, to white. The color is more irregular than the composition, bands, blotches, and mottlings diversifying the structural units. Fossils are rare. In its representative parts they are all of land plants and animals (except, of course, the fossils derived from earlier formations).

*Origin.* The preferred interpretation of the Lafayette formation is as follows: At the opening of the Pliocene, the Appalachian tract is supposed to have been affected by broad, flat, intermontane valleys, mantled by a deep residual soil and subsoil. The Piedmont tract to the east is supposed to have been a peneplain near sea-level. It is assumed that the upward bowing was felt first in a relatively narrow belt along the axis of the mountain system, that the rise was gradual, and that the rising arch increased in width as time advanced. The first up-bowing rejuvenated the head waters of the streams from the mountain tract, and the surface, with its heavy mantle of residual earth, readily furnished load to the streams. When they reached that portion of the peneplain not yet affected, or less affected, by the bowing, they dropped part of their load (at *b*, Fig. 501). With continued rise, the zone of deposition is supposed to have been shifted seaward, and the deposits already made were eroded and the eroded material was redeposited farther from

the mountains and nearer the sea (at $b'$, Fig. 501). Thus the process is presumed to have continued till the border of the upraised tract passed beyond the present sea-coast. The whole deposit within the area of the present land was then eroded, and the erosion had reached a notable degree of advancement before the first known glacio-fluvial deposits were laid down. This hypothesis of the origin of the formation postulates that the shallow valleys of the coastal plain were filled with sediment, and that later the deposits spread rather generally over the low divides between them. In the region of deeper valleys, such as the Tennessee, the valleys were only partly filled. It has been assumed generally that the formation was once

Fig. 501. Illustrating the progressive stages of arching described in the text, and the attendant shifting zones of deposition; *s-s*, sea-level; *a*, original peneplaned surface with graded slope to sea-coast; $a'$, $a''$, $a'''$, successive stages of arching; $b$, $b'$, $b''$, $b'''$, successive sites of deposition corresponding to stages of arching $a$, $a'$, $a''$, $a'''$. In the stage of arching represented by $a''$, the right hand portion of the previous site of deposition is lifted and becomes a part of the area of erosion. The same process is carried farther in the next stage represented by $a'''$.

continuous east of the mountains where patches only now remain; but it may be that the higher divides were never covered by the formation.

The removal and re-deposition of material as suggested by Fig. 501 is regarded as an important part of the interpretation of the formation. Erosion and re-deposition of the material did not cease with the Lafayette epoch, but have been in progress ever since, and the derivatives so closely resemble the parent formation in structure and material that their separation is difficult.

If it shall be shown ultimately that the seaward portions of the Lafayette, now concealed or unstudied, are marine, the preceding hypothesis would need to be modified only by supposing that as the sources of the streams was bowed up, the coastal border of the plain was submerged. In this case, there should have been estuarine formations in the seaward ends of the valleys.

The chief alternative view relative to the origin of this formation regards it as marine,[1] deposited during a stage of submergence essentially co-extensive with the area of the formation. This hypothesis has been tried out by geologists of wide familiarity with

[1] McGee, 12th Ann. Rept., U. S. Geol. Surv.

the phenomena, and abandoned as untenable even where conditions seem most to favor it. The objections to it are (1) the absence of marine fossils; (2) the presence of structural features not indicative of typical marine deposits; (3) the chemical condition of the formation, particularly the high and very unequal oxidation and the meager hydration; (4) the topographic relations of the formation, especially the lack of any approach to horizontality in its upper limit; and (5) the absence of shore phenomena.

### *Marine Formations*

**The Atlantic coast.** If fossils be the test, Pliocene beds of marine origin have little development on the eastern side of the continent. In Florida only (Caloosahatchie beds) have beds containing marine fossils any considerable extent at the surface, though small patches are known farther north. They may be parts of a continuous formation, chiefly concealed. The time relations of these marine Pliocene beds to the Lafayette are undetermined. Pliocene beds of marine origin have not been identified certainly between Florida and Texas, but they cover considerable areas farther south, as in Yucatan.

**The Pacific coast.**[1] Marine sedimentation along this coast was confined to narrow limits (Fig. 502). The deposits are chiefly clastic. Their maximum known thickness is found south of San Francisco, where about 4,000 feet of strata (*Merced* series) are exposed.[2] The non-marine part of the system (*Paso Robles* formation) is as thick in the San Joaquin valley.

### *Crustal Movements*[3]

The tendency to crustal movements, both warping and faulting, which had characterized the western part of the continent since the close of the Mesozoic, seems to have continued at least intermittently through the Pliocene. Perhaps these movements were in many places no more than continuations of those begun earlier.

About the close of the period, movements were extensive and

[1] Arnold, Ralph, Jour. Geol., Vol. XVII.

[2] Lawson, Science, Vol. XV, 1902, p. 410, and Hershey, Am. Geol., XXIX, p. 359, give the Pliocene of California greater thicknesses.

[3] LeConte, Am. Jour. Sci., Vol. XXXII, p. 167, 1886, Bull. Geol. Soc. Am., Vol. II, p. 329, Jour. Geol., Vol. VII, p. 546, 1899; Hershey, Science, Vol. III, p. 620, 1896, and Dutton, Mono. I, U. S. Geol. Surv.

great, resulting in increased height of land. The region covered by the Lafayette formation was elevated relatively, and perhaps somewhat deformed. The coast line was probably farther east than now, perhaps at the edge of the continental shelf. To this epoch the submerged continuations of the St. Lawrence, Hudson, Delaware, Susquehanna, and Mississippi valleys are commonly referred. From these submerged valleys it was formerly assumed that the land along the Atlantic seaboard must have stood 2,000 to 3,000 feet, or perhaps even 7,000 to 12,000 feet[1] above its present level, to allow of their excavation; but it may not be necessary to postulate such extraordinary changes of level. Continental creep (p. 350) along the slope between the continental platforms and the ocean basins may have lowered the valleys notably as it carried them seaward, if such creep is a fact.

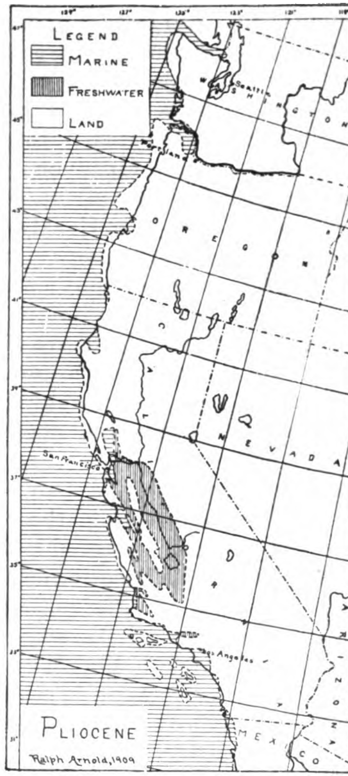



Fig. 502. Map showing supposed distribution of land and water on the Pacific coast of the United States during the Pliocene period. (Ralph Arnold.)

In the Mississippi basin also there was notable elevation at the close of the period, though probably less than has sometimes been estimated. It seems possible, or perhaps even probable, that the evolution of the principal physiographic features of the interior, so far as due to erosion, is post-Pliocene.

In the west, too, there were notable closing-Tertiary movements. The plateau region was in process of uplift, periodically, throughout the Tertiary, during which it has been estimated to have undergone an elevation of 20,000 feet (Dutton), and a degradation of

[1] Spencer, Am. Jour. Sci., Vol. XIX, 1905.

12,000, leaving it 8,000 feet above sea-level. How much of this is assignable to the close of the Pliocene is uncertain. It was Dutton's view that the Colorado plateau was so elevated at this time as to rejuvenate the Colorado River, and that the cutting of its inner gorge some 3,000 feet (maximum) below the outer (Fig. 73), was the work of later times. More recent studies indicate that even the outer and broader part of the valley is younger than formerly was thought, and raise a question as to whether the inner gorge is not the result of rock structure, rather than of a distinct and later uplift.[1] If the whole of the canyon is post-Pliocene, the elevation of the region since the close of the Tertiary must have been several thousand feet. The later elevations in this region, largely by blocks, were so recent that many of the fault scarps are distinct, and independent of stratigraphy and drainage.

In the basin region, faulting and deformation [2] gave rise to depressions between the Sierra Nevada and the Wasatch Mountains, preparing the way for two great Pleistocene lakes (Bonneville and Lahontan). It is probable that many other faults between the Rockies and Sierras were developed at the same time, and in many cases the movement seems to have been along fault planes established earlier.

In the Sierra region, the post-Tertiary (or late Tertiary?) uplift was still more marked.[3] Not only the deep canyons of these mountains, but all the scenery of the high Sierras is post-Tertiary.[4]

Still nearer the Pacific, notable changes marked the transition to the Pleistocene. In some parts of southern California (Los Angeles County) marine Pliocene beds are said to occur up to altitudes of 6,000 feet, and in others (San Luis Obispo), there was folding (Fig. 492) and faulting, while the shore-line was pushed out toward the edge of the continental shelf. There are submerged valleys along the Pacific coast, as along the Atlantic, but their excavation has been referred to a time earlier than the close of the Tertiary.

In Washington, present knowledge points to the early Pliocene as a time of prolonged erosion. The crests of the Cascade Moun-

[1] Huntington and Goldthwaite, Bull. Mus. Comp. Zoöl. Geol. Ser., Vol. VI, p. 252; and Davis, ibid., Vol. XXXVIII.

[2] King, U. S. Geol. Expl. of the 40th Parallel, Vol. I, p. 542.

[3] LeConte, op. cit., and Diller, 14th Ann. Rept., U. S. Geol. Surv.

[4] The beginning of the re-elevation of the Sierras, after peneplanation, was mid-Miocene.

tains seem to represent remnants of a deformed peneplain, which, carried to the east and south, is continuous with an erosion plain which cuts across strata (Ellensburg formation) of late Miocene[1] age. The planation must, therefore, have been later than that part of the Miocene period represented by the Ellensburg formation. At least the early part of the Pliocene period, if not most of it, would seem to have been necessary for the accomplishment of this great planation, so that the peneplain can hardly be thought to antedate late Pliocene time. If this is correct, the main features of the present topography of this rugged region are the result primarily of Pleistocene erosion on the peneplain uplifted and deformed in Pliocene time, or later, and secondarily of vulcanism, which has built up the great volcanic piles (Rainier and others) which affect the region. In British Columbia also, the Pliocene is thought to have been primarily a time of erosion.

Deformative movements of the orogenic type seem not to have been common at the close of the Pliocene, but such movements affected the Santa Cruz Mountains of California, where Miocene (Monterey) and Pliocene (Merced) beds were deformed together.[2]

On the whole, the close of the Pliocene must be looked upon as a time of great deformation, a critical period in the history of North America. New lands were made by emergence from the sea, and old lands were deformed and made higher; new mountains were made, and old ones rejuvenated; streams were turned from their courses in some places, and nearly everywhere started on careers of increased activity. The fact that such notable changes, with increased elevation of land, occurred during the epoch next preceding the glacial period, is one of the considerations which led to the once widespread belief that elevation was the cause of the climate of the latter period. While there may be a connection between the two things, it was probably not in the simple and commonly accepted sense.

### *Volcanic Activity*

The volcanic activity of preceding periods continued into the Pliocene, and became somewhat pronounced near the end of the period in different parts of the western Cordillera. Some of the

[1] Smith, Ellensburg, Wash., folio, U. S. Geol. Surv.; and Willis and Smith, Professional Paper 19, U. S. Geol. Surv.

[2] Ashley, Jour. Geol., Vol. III, p. 434.

late igneous formations of the Sierras, and perhaps of northern California,[1] belong to this time, and probably some of those of nearly or quite every other state west of the Rocky Mountains. Many of the prominent volcanic peaks of the west date from this time or later, and represent the later phases of the prolonged period of volcanic activity, just as the great lava flows and intrusions represent the earlier. Many lesser cones belong to the same period.

### *Foreign*

From considerable areas of Europe covered by water during the Miocene, the waters retreated late in the period or at its close; but the sea covered southern and southeastern England, Belgium, and parts of France during at least some portion of the Pliocene, and still more extensive areas of the present continent about the Mediterranean. Beyond the inland margins of the marine Pliocene, there are contemporaneous beds of terrestrial origin. In southeastern Europe, brackish and salt lakes came into existence, as shown by the fossils and the local deposits of salt and gypsum. In some places, as in the Vienna basin, brackish water beds below grade up into fluviatile beds above.

In Italy only do Pliocene beds attain massive development. Along the Apennines their thickness has been estimated at from 1,600 to 3,000 feet, and in Sicily 2,000 feet. Limestone as well as clastic beds enter into the system, which occurs up to heights of 3,000 feet.

Marine Pliocene is known in Egypt, where the sea is thought to have extended up the Nile to Assuan. The formation of the basins of the Red Sea and the Gulf of Suez has been assigned to this period. These depressions have been thought to be down-faulted blocks.

## LIFE

**Land plants.** During the Pliocene there was a further sorting out of the mixed flora of previous periods, and the southerly segregation of what are now tropical and subtropical plants continued; but in Europe generally there was still much commingling of species now separated geographically.

**Land animals.** Three important features characterized the Pliocene history of mammals: (1) A notable intermigration between the continents, including North and South America; (2) the begin-

[1] Hershey, Jour. Geol., Vol. X, pp. 377–392.

ning of the present divergence between Old and New World types; and (3) the culmination and perhaps initial decline of the mammals, except those domestic species protected by man.

The intermigrations of the early part of the period were made possible by the land connections brought about by deformative movements. The extent of the connection of North America with Asia at the northwest and with Europe at the northeast respectively, is uncertain, but there is conclusive evidence that there were good migratory routes for land mammals in both directions during a part of the period. There are also strong hints that the connection afforded passage for some species, but not for others, due perhaps to the increasing cold toward the end of the period. This low temperature, with its effect on intermigration, was perhaps the chief factor in developing the difference between the mammals of the Old World and the New.

The connection between North and South America introduced a biological movement of much interest. There appears to have been no effective isthmian thoroughfare for land animals between the earliest Eocene and the Pliocene. During the Eocene connection, a few North American mammals seem to have sent representatives into South America, and these had evolved there on distinctive lines in the interval. A remarkable group of sloths, armadillos, and ant-eaters had developed from an edentate stem; strange hoofed animals of orders unknown elsewhere had arisen from some very primitive ungulate form; and the monkeys of the South American type had evolved probably from a North American Eocene lemuroid. That the connection of the continents in the Eocene was only partial or temporary seems to be implied by the absence in South America of most of the great North American groups. The absence of proboscidians in South America implies lack of connection between that continent and Africa, where these forms developed during the Eocene and Miocene; but the many marsupials of South America, similar to those of Australia, imply either land connection between those continents, or striking parallel evolution. The South American mammalian fauna at the beginning of the Pliocene is a striking instance of evolution on a large scale in comparative isolation, and in relative freedom from the severe stimulus of effective competition, powerful carnivores, and shifting geographic relations.[1]

[1] Reports of the Princeton University expedition to Patagonia, 1896–99

When connection between the two Americas was made in the Pliocene, the fauna of each continent invaded the other. Horses, mastodons, deer, carnivores, and tapirs from the northern continent went to the southern, while gigantic sloths from the south came to our continent, though they did not maintain themselves long.

The *herbivores* had the foremost place among mammals; both the odd- and even-toed ungulates evolved their present orders, and many of their present genera. They were represented also by many genera and species which are now extinct. The evolution of the horse was advanced to the existing genus *Equus*. Giraffes and giraffe-like animals, some of them of great size, invaded southern Europe and Asia, probably from Africa.

The giants of the period were the *proboscidians*. The extinct *Dinotherium* was widely distributed in Europe and has been found in India, but is not known to have reached America. Mastodons seem to have lived in all the continents, but it is doubtful whether elephants reached America before the Pleistocene. They appear to have flourished in Europe, and, with the associated rhinoceroses and hippopotamuses, gave the European Pliocene fauna an African aspect.

*Carnivores* throve and perhaps gained on the herbivores; at any rate they put a severe tax on the herbivores, forcing further progress in the line of alertness, sagacity, speed, and defense, and gaining similar qualities themselves.

Great interest attaches to the development of the *primates* (monkeys, apes, man), but the data on this point are likely to remain limited until the tropical regions of the Old World, where the chief evolution of this group seems to have taken place, are more fully studied. No remains of lemuroids or of their descendants have been found in the Pliocene of North America, and those of Europe are from the middle and southern parts of the continent, perhaps implying that northern Europe was too cold for these animals.

Some years ago a man-like skeleton was found in what were then regarded as Pliocene deposits in Java, and named *Pithecanthropus erectus*. The find included the roof of a skull, two molar teeth, and a femur. The form of the femur indicates that its possessor walked erect. The forehead was low and the frontal ridge prominent, and in general the characteristic features were intermediate between those of the lowest men and the highest apes, as shown in Fig. 503. The size of the brain was about two-thirds that of an average man.

The interpretation of this find has elicited much difference of opinion. By some the bones are thought to be those of an abnormal man; by others, those of an ancestral type between man and his remote ancestry. Recent studies throw doubt on the Pliocene

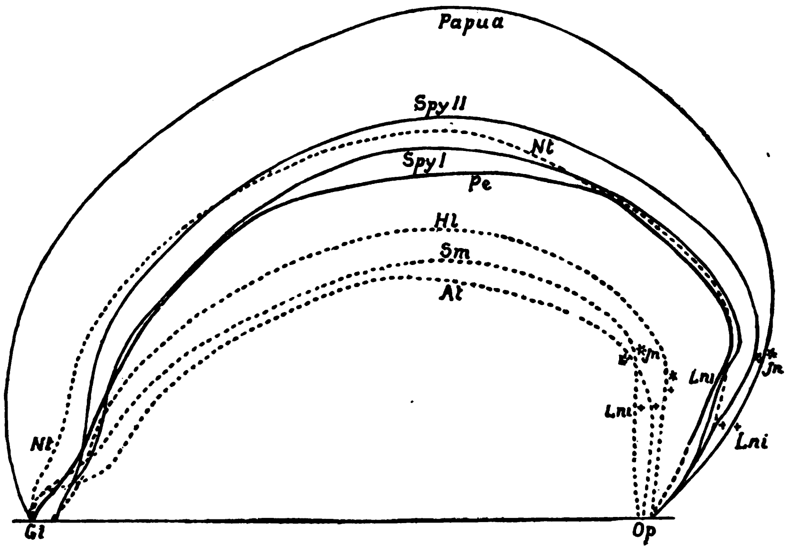



Fig. 503. Profile of the skull of the *Pithecanthropus erectus* (line *Pe*) compared with profiles of the lowest men and highest apes; *Spy I* and *Spy II*, the men of Spy; *Nt*, the Neanderthal man; *Hl*, a gibbon (*Hylobates leuciscus*); *Sm*, an Indian ape (*Semnopithecus maurus*); and *At*, a chimpanzee (*Anthropopithecus troglodytes*). (After Marsh.)

age of the beds in which the fossil was found.[1] They may be Pleistocene.

**Marine life.** The record of marine life on the Atlantic coast of America is meager, but it appears that species which then ranged from Bering Sea to the north Atlantic are now confined to temperate latitudes.[2] On the coast of California the early Pliocene faunas indicate a temperature lower than that of the Miocene, while the later Pliocene faunas point to sub-boreal conditions.[3] On the other hand, Pliocene fossils from Alaska (vicinity of Nome) indicate for this locality a climate similar to that of north Japan and the

[1] Berry, Science, Vol. XXXVII, p. 418.
[2] Dall, Jour. Geol., Vol. XVII.
[3] Arnold, Ralph, Jour. Geol., Vol. XVII.

Aleutian Islands, where the sea remains unfrozen. Pliocene fossils from the northwest coast of Iceland indicate a temperature no colder than 42° (mean), where conditions are now arctic. The apparent lack of harmony between the phenomena of California and higher latitudes may perhaps be due to the different horizons from which the fossils come, the fossils from the different places recording the climate of different parts of the period.

Certain fossils of Japan and California indicate intermigration, or migration from a common center, some time during the period.

# CHAPTER XXIX

## THE PLEISTOCENE OR GLACIAL PERIOD

### FORMATIONS AND PHYSICAL HISTORY

The distinguishing feature of this period is its extensive glaciation. Thick sheets of ice, having the slow movement of glaciers, covered six or eight million square miles of the earth's surface where climates had been mild not long before.

More than half the area known to have been glaciated during this period was in North America, and more than half of the remainder in Europe.

**North America.** Nearly half of North America was covered by ice (Fig. 504), and strangely enough it was the plain, rather than the mountainous part, which had most ice. Three principal *centers* whence ice moved have been recognized on the continent,[1] the Labradorean, the Keewatin, and the Cordilleran. Spreading from these centers, ice-sheets covered some 4,000,000 square miles. From the Labradorean center, the extension was notably greatest to the southwest, and in this direction the limit is some 1,600 miles from the center of dispersion, in latitude about 37° 30′. The extension of the Keewatin ice-sheet to the southward was scarcely less. It found its limit in Kansas and Missouri, about 1,500 miles from its center, while to the west and southwest it extended 800 to 1,000 miles toward the Rocky Mountains. One of the notable features of the ice dispersion was the great extension of the Keewatin sheet westward and southwestward over what is now a semi-arid plain, rising in the direction toward which the ice moved, while glaciers from the mountains on the west pushed eastward but little beyond the foothills.

The Cordilleran ice-sheet is less simply defined. Much of it occupied a plateau hemmed in by mountains; but plateau glaciation was complicated by extensive mountain glaciation of alpine type.

[1] A fourth center (*Patrician*) has been suggested by Tyrrell, southwest of Hudson Bay, and still another by Wilson, in the extreme East. Wilson, *The Glacial History of Nantucket and Cape Cod.*

The southerly lobes of the complex body of ice crossed the boundary of Canada into the United States. The plains of Alaska seem to have been largely free from glaciation even when the waters of the

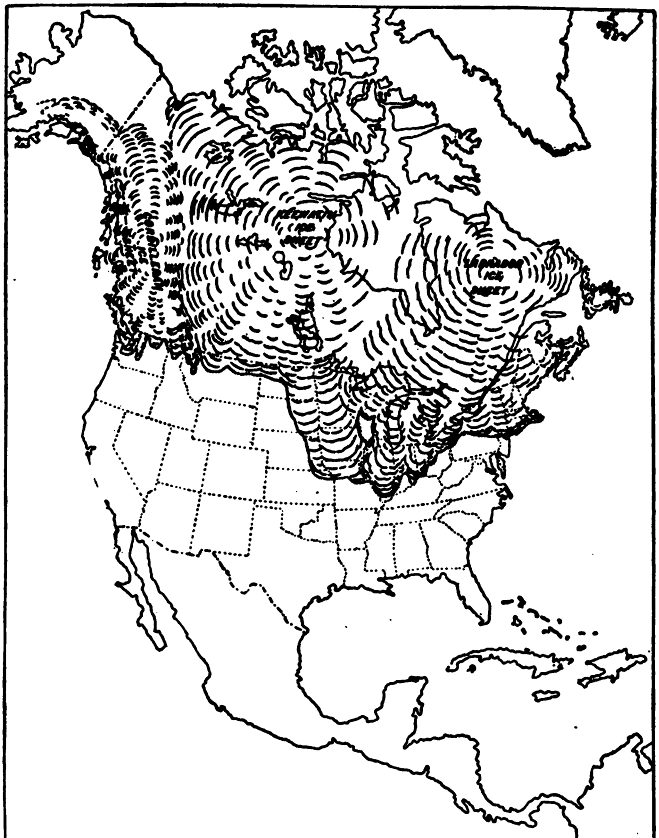


Fig. 504. Sketch-map showing the North American area covered by ice at the stage of maximum glaciation.

Ohio and the Missouri, 2,000 miles farther south, were being turned from their courses by the ice-sheets.

South of the more or less continuous Cordilleran glaciation of the north, *local glaciers* were widely distributed in the western mountains, even down to New Mexico, Arizona, and southern California.

They were larger at the north and smaller at the south. Of glaciation in the mountains of Mexico little is known.

*Greenland* was glaciated more extensively than now. *Newfoundland* seems to have had its own ice-sheet, and the same was probably true of Nova Scotia, and probably of the peninsula between the Bay of Fundy and the lower St. Lawrence.

**Other continents.** South of the ice-sheet of Europe (Fig. 505), great glaciers descended from the Alps to the lowlands in all direc-

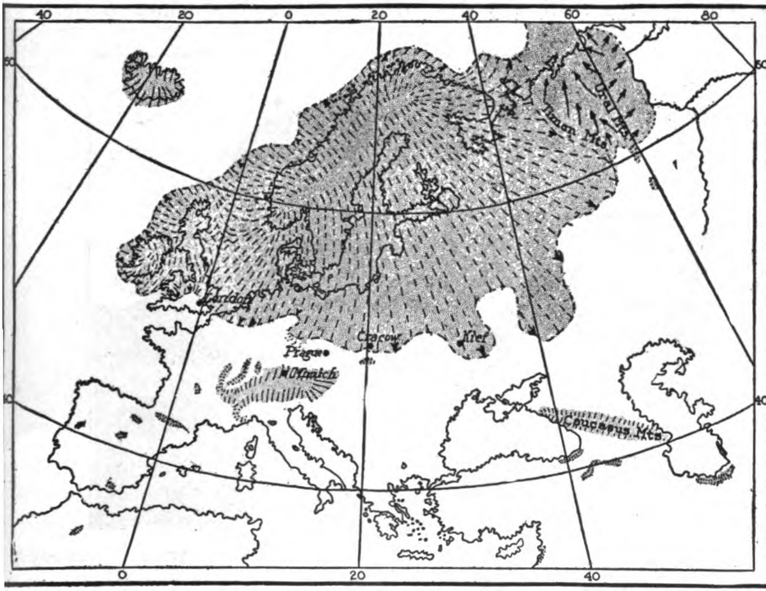



**Fig. 505.** Sketch-map showing the area of Europe covered by the continental glacier at the time of its maximum development. (Jas. Geikie.)

ions. Iceland was buried in ice, and even Corsica had glaciers. In Asia glaciers larger than those of to-day affected all the higher nountains, and ice-sheets existed in some of the more northern ands. In tropical regions, there were glaciers in mountains where ione exist now, and in mountains where there are glaciers now, the ce descended to levels 5,000 feet or more below its present limits. The southern hemisphere was affected less than the northern, but he higher mountains generally bore glaciers, and even mountains vhich were not very high, as the southern Andes, had glaciers which

reached the plains outside the mountains. Antarctica is assumed to have been buried beneath ice as now.

*The Criteria of Glaciation*

The area of North America which was overspread by ice is covered by a mantle of clay, sand, and bowlders which, taken together, constitute the *drift*. The various lines of evidence which have led to the general acceptance of the glacial theory have to do with (1) the drift, (2) the surface of the rock which underlies

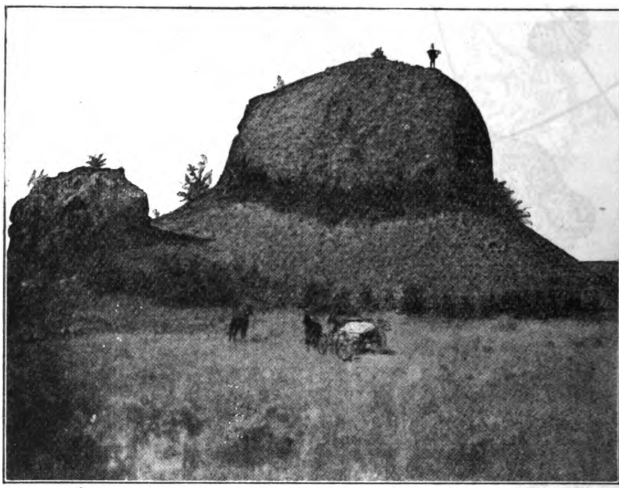


Fig. 506. "Pilot Rock," a glacial bowlder near Coulee City, Wash. (Garrey.)

it, and (3) the relations of the drift to the bed. Some of the principal considerations are the following:[1]

1. **Constitution.** One of the distinctive characteristics of the drift is its heterogeneity, both physical and lithological. It is made up at one extreme, of huge bowlders (Fig. 506), and at the other of fine earthy matter. Between these extremes there are materials of all sizes, and the proportions of coarse and fine are subject to great variations. Coarse materials are, on the whole, most abundant in regions of rough topography, where the underlying and neighboring formations in the direction from which the drift came are resistant;

[1] Jour. Geol., Vol. II, pp. 708–724 and 807–835, and Vol. III, pp. 70–97.

fine materials are most abundant where the underlying formations and neighboring formations in the direction from which the drift came, are weak. The fine part of the drift is made up largely of the same materials as the gravel and bowlders, but of these materials in a fine state of subdivision. The coarse and the fine materials are, as a rule, mixed without trace of assortment or arrangement. The drift of any locality is likely to contain rock material from every formation over which the ice which reached that locality had passed; but the larger part of the drift of any place is from formations near

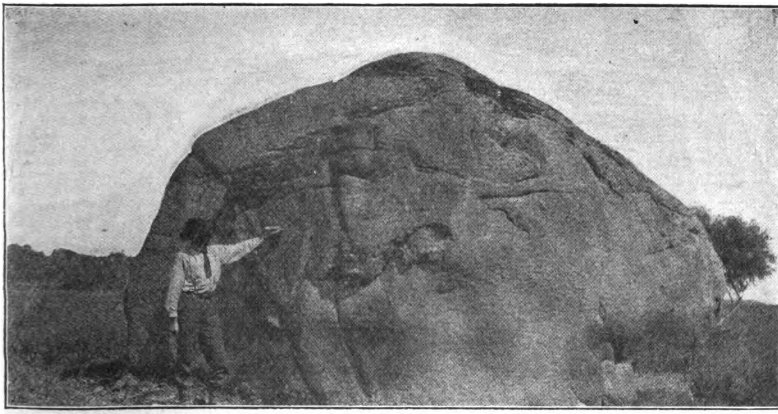


Fig. 507. A large bowlder in northwestern Illinois. (Carman.)

at hand. Over large areas it is probable that 75% of the drift was not moved 50 miles.[1] No agent except glacial ice makes deposits with these characteristics.

2. **Bowlders of the drift.** Many of the bowlders and smaller stones of unstratified drift have smooth surfaces, but they are not generally rounded. Many are subangular, and the wear which they have suffered was effected by planing and bruising, rather than by rolling (Figs. 147 and 508). Some of these planed, subangular bowlders and stones are distinctly marked with one or more series of lines or *striæ* on one or more of their faces. The lines of each series are parallel, but those of different sets may cross at any angle. By no means all the stones of the drift show striæ. They are rarely seen on those which have lain long at the surface, and they are more common on the less resistant sorts of rock, such as limestone. No

[1] The Local Origin of the Drift, Jour. Geol., Vol. VIII, p. 426.

depositing agent except glaciers habitually marks the stones which it deposits in this way.

3. **Structure.** The larger part of the drift is unstratified, but a considerable part is stratified, some of it irregularly. The unstratified drift (Fig. 509) or *till* (for some of it the name *bowlder-clay* is appropriate) has no orderly arrangement of its parts. The structure of the stratified drift (Fig. 511) shows that it was deposited

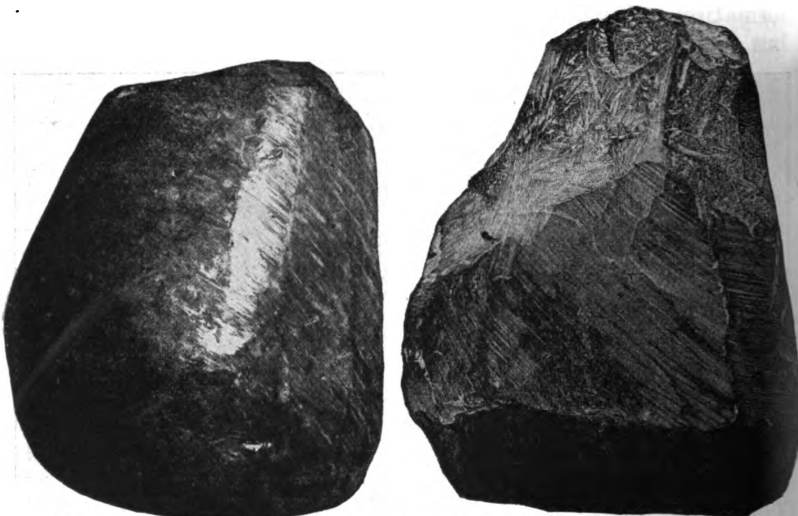


Fig. 508. Stones of the drift, striated and beveled by glacial wear. (U. S. Geol. Surv.)

by water, which doubtless sprang, in large part, from the melting of the ice. Either of the two great types of drift, the stratified and the unstratified, may overlie the other, or the two may be interbedded. The association of the two is such as to demonstrate their essential contemporaneity of origin. No agents but glacial ice and glacio-fluvial waters could have brought about such relations between the stratified and unstratified drift over such extensive areas.

4. **Distribution.** The distribution of the drift is essentially the same as that of the ice-sheets and glacial waters; but apart from this general fact, several special features may be noted. (a) Within the area of its occurrence, the drift is measurably independent of topography. That is, its vertical range is as great as the relief of the surface itself. Within the state of New York, for example, it

ranges from sea-level to the tops of the Adirondacks, nearly 5,000 feet above. It is found on hills and in valleys, and on plains, plateaus, and mountains, indiscriminately, though not usually in equal amounts. (b) Locally the drift is so disposed as to make the surface rougher than it would be otherwise, and in other places so as to give it less relief (Figs. 512 and 513). (c) In constitution it is measurably independent of present drainage basins. Thus, mate-

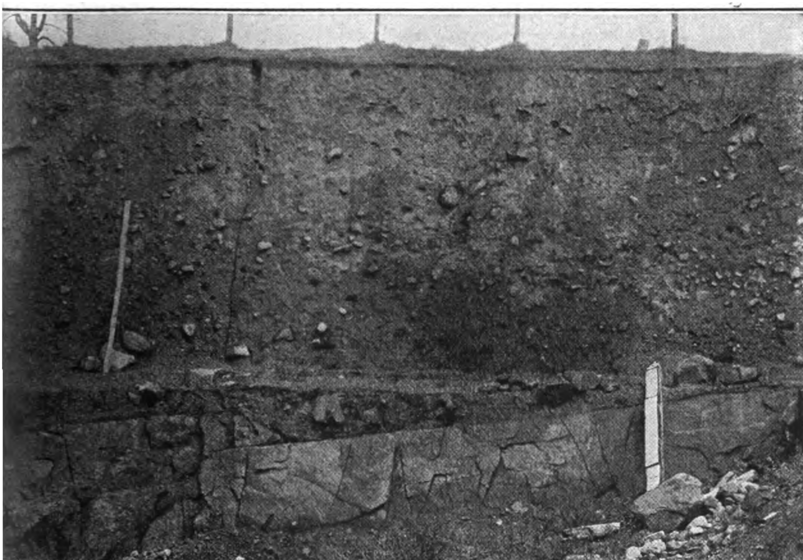


Fig. 509. A section of unstratified drift, till or bowlder clay, on bed-rock. Newark, N. J. (N. J. Geol. Surv.)

rials from one drainage basin are found in the drift of other drainage basins so commonly as to make it clear that present divides did not constitute divides to the ice. (d) Various sorts of material in the drift at certain points are so related to their sources as to make it clear that they were carried upwards, in some cases hundreds of feet, above their original sites. (e) A considerable area in southwestern Wisconsin, and the adjacent parts of Illinois, Iowa, and Minnesota, is without drift. This driftless area is neither notably higher nor lower than its surroundings, and glacial ice seems to be the only agent which could have spared it, while covering its sur-

roundings. (f) Stratified drift extends beyond the unstratified in the direction in which the ice was moving, especially in valleys and on low land. This is the work of running water.

5. **Topography.** Among the characteristic features of the topography of the drift are: (a) Depressions without outlets, and (b) associated knobs, hills, and ridges, similar in size to the depressions (Figs. 168 and 514). Many of the depressions contain ponds

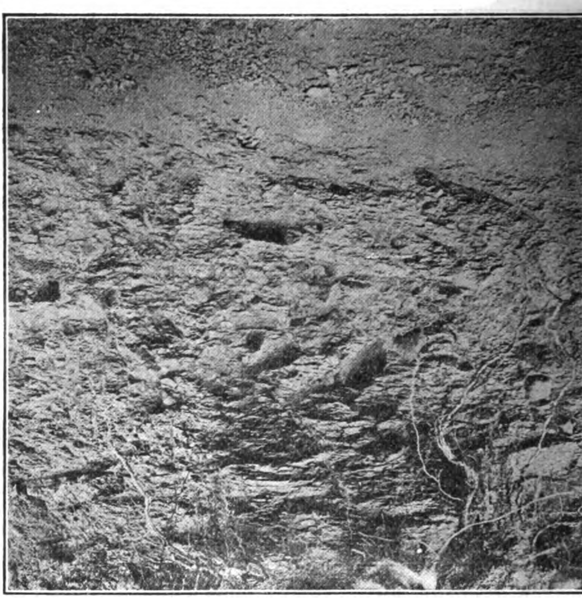


Fig. 510. Foliated till. (Photo. by Jefferson.)

or lakes. The surface of some parts of the drift, on the other hand, is nearly plane.

6. **Thickness.** The drift ranges from zero to more than 500 feet in thickness, and the variations may be great within short distances. The drift may be thick on hills and thin in valleys, or, more commonly, the reverse. No agent besides glaciers habitually leaves its deposits so unequally distributed, and in such disregard of pre-existing topography.

7. **Contact with underlying rock.** The plane of contact between the drift and the rock beneath is generally, though not always,

Fig. 511. A section of stratified drift.

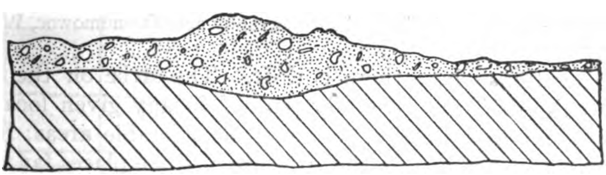


Fig. 512. Diagram to show how drift may be so disposed as to increase the relief of the surface. This should be compared with the following figure.

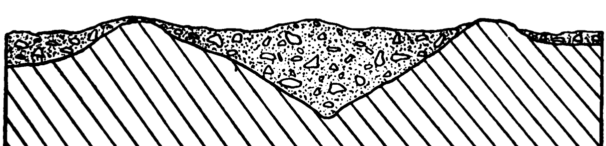


Fig. 513. Diagram to illustrate how drift may decrease relief.

sharply defined, and the surface of the rock is likely to be fresh and firm (Fig. 145). This relation is in contrast with that between mantle rock and the underlying formations where there is no drift (Fig. 152).

8. **Striation and planation.**[1] The rock surface beneath the drift, and especially beneath the unstratified drift, is in many places polished, planed, striated (Fig. 145), and grooved. These features are widespread throughout the drift-covered area, and they appear

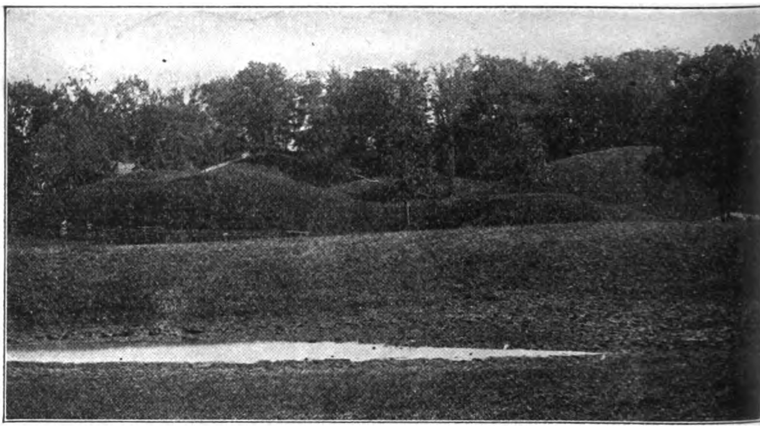


Fig. 514. Terminal moraine topography near Oconomowoc, Wis.

at all elevations where there is drift. The striæ on the bed rock beneath the drift are generally parallel in any given locality, and tolerably constant in direction over considerable areas; but when large areas are considered, the striæ are in some places far from parallel. Their direction corresponds with the direction in which the drift was transported.

9. **Shapes of rock hills.** Many rock knolls which were left bare when the ice retreated show peculiarities of form and surface which are distinctive. They were worn more on the side from which the ice approached (the stoss side) than on the other (Fig. 153). Bosses of rock which do not show notably unequal wear show distinct smoothing. Projecting glaciated knolls of rock which show the characters seen in Fig. 167, p. 162, are known as *roches moutonnées*.

[1] Seventh Ann. Rept., U. S. Geol. Surv., has a full discussion of this topic.

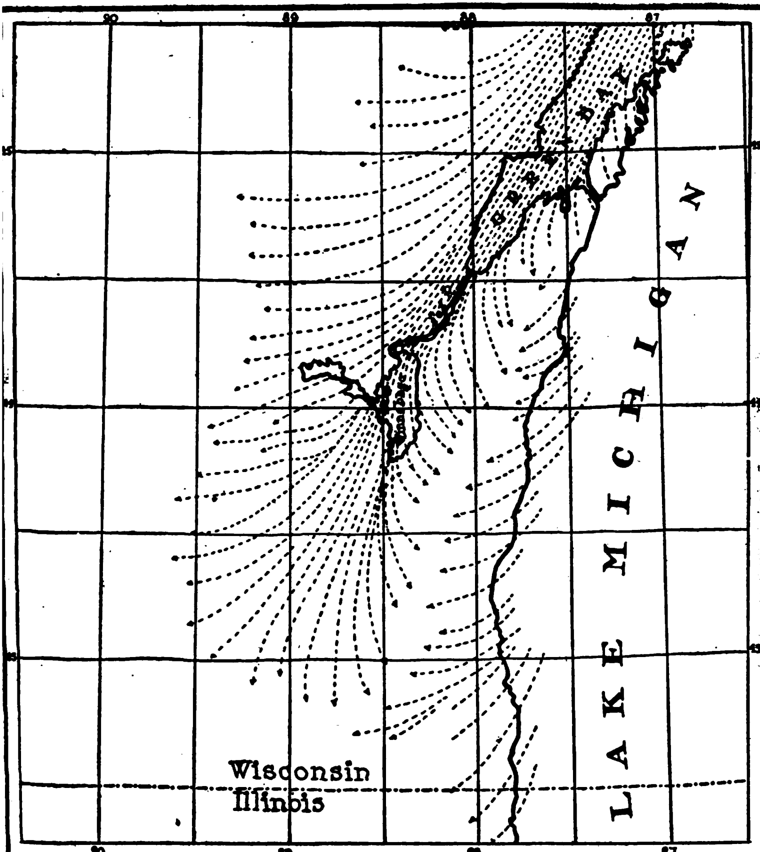



Fig. 515. The radiation of striæ in the area of the Green Bay glacial lobe and in the west part of the Lake Michigan lobe, during the last glacial epoch.

The true theory of the drift must explain all the foregoing facts and relations. Any hypothesis which fails to explain them all must be incomplete, and any hypothesis with which these facts and relations are inconsistent must be false. Geologists are now agreed that glacier ice, supplemented by the agencies which it calls into being, is the only agent which could have produced the drift. This does not preclude the belief that at various times and places in the course of the ice period, icebergs were formed, or that locally and

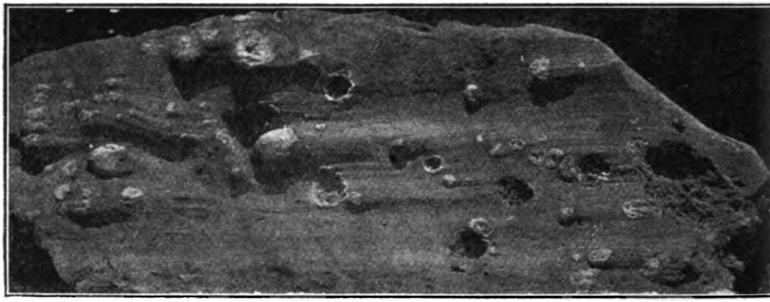


Fig. 516. Small protuberances of rock showing the effect of ice wear. Glacial knobs and trails. Movement of ice from left to right. The projections consist of chert in limestone. Near Darlington, Ind. (U. S. Geol. Surv.)

temporarily they played an important rôle. It does not preclude the idea that, contemporaneously with the production of the great body of the drift by glacier ice, the sea may have been working on some parts of the present land area, modifying the deposits made by ice and ice drainage. The glacial theory does not deny that rivers produced by the melting of the ice were an important factor in transporting and depositing drift, both within and without the ice-covered territory. It does not deny that lakes, formed in one way and another through the influence of ice, were locally important in determining the character and disposition of the drift. Not only does the glacier theory deny none of these things, but it distinctly affirms that rivers, lakes, the sea, and icebergs must have co-operated with glacier ice in the production of the drift, each in its appro-

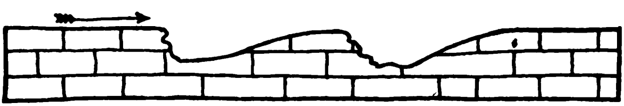


Fig. 517. Diagram to show the effect of ice wear on slight depressions in the surface of rock.

priate way and measure, and that after the disappearance of the ice and the ice-water, the wind had some effect on the drift before it was clothed with vegetation.

*Development and Thickness of the Ice-sheets*

The development of glaciers from snow-fields has been discussed (pp. 124–7). If the expansion of the ice-sheets was due prin-

cipally to movement from a center or centers, the ice at these centers must have been prodigiously thick, for in the course of its progress it encountered and passed over hills, and even mountains, of considerable height. In the vicinity of elevations which it covered, its thickness must have been at least as great as the height of these elevations above their bases.

If the centers of the North American ice-sheets remained the *centers of movement* throughout the glacial period, and if the degree of surface slope necessary for movement were known, the maximum thickness of the ice could be calculated. But it is probable that the centers of the ice-sheet did not remain the effective centers of movement. If the fall of snow toward the margin of the ice-sheet greatly exceeded that at its center, as it probably did, a belt near the

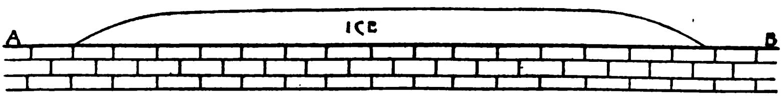



Fig. 518. Diagram to illustrate the surface configuration of a great ice-sheet, according to the conception here presented. The central part is relatively flat, and the margins have steep slopes.

margin, rather than the geographic center of the field, may have controlled the marginal movement of the ice. With excess of accumulation near the border, the slope of the surface near the edge might be relatively great, while it was slight in the center of the field, as shown by Fig. 518. Under these conditions, the maximum thickness of the ice-sheets might be notably less than if the geographic center remained the effective dynamic center.

No sufficient data are at hand for determining with accuracy the average slope of such an ice-sheet as that which covered our continent, but something is known of its slope at certain points. Near Baraboo, Wisconsin,[1] the edge of the ice at the time of its maximum extension in that region lay along the side of a bold ridge, the axis of which was nearly parallel to the direction of ice movement. The position of the upper edge of the ice against the slope of the ridge is sharply defined. For the last 1¾ miles, its average slope was about 320 feet per mile. This was at the extreme edge of the ice, where the slope was greatest. In Montana, the slope of the upper surface of the ice for the 25 miles back from its edge has been estimated at 50 feet per mile.[2]

[1] Jour. Geol., Vol. III, p. 655.
[2] Calhoun, Jour. Geol., Vol. IX, p. 718.

The southern limit of drift in Illinois is not less than 1,500 or 1,600 miles from the center of movement. An average slope of even 25 feet per mile for 1,600 miles would give the ice a thickness of 40,000 feet at the center, the slope of the surface on which the ice rested being disregarded. This thickness seems incredible. Even an average slope of 10 feet per mile would give a thickness of about three miles at the center. If by reason of relatively great precipitation near its margins, the only part of the ice-cap which had considerable slope was its outer border (Fig. 518), a lesser maximum thickness would suffice.

**Stages in the history of an ice-sheet.** The history of an ice-sheet which no longer exists involves at least two distinct stages. These are (1) the period of growth, and (2) the period of decadence. If the latter did not begin as soon as the former was completed, an intervening stage, representing the period of maximum ice extension, is to be recognized. In the ice-sheets of the glacial period, each of these stages was probably more or less complex. The general period of growth was doubtless interrupted by short intervals of decadence, and the general period of decadence by brief intervals of growth. In the study of the work accomplished by an ice-sheet, it is of importance to distinguish between these main stages.

### *Work of Ice-sheets*

*Erosion* and *deposition* were the two great phases of ice work (p. 147 *et seq.*). The surface over which the ice-sheets moved probably had an erosion topography, and was covered by a layer of mantle rock. The ice removed the mantle of decayed material, and cut deeply into the undecayed rock beneath. By its erosion, the ice modified the topography to some extent, for weaker formations were eroded more than resistant ones, and topography favored more forcible abrasion at some points than at others. On the whole, the topographic effect of glacial erosion was probably to soften the surface contours, without diminishing the relief.

The second great result of the ice-sheets was the deposition of the drift. Some of it was deposited while the ice-sheets were growing, some of it after they had attained their growth, and some of it while they were declining. Some of it was deposited beneath the body of the ice, and some at its edge. Where it was thick, the drift altered the topography notably, especially where the relief of the underlying rock was slight.

**Formations made by ice-sheets.**[1] The drift formations fall chiefly into three categories, (1) those made directly by the ice (unstratified), (2) those made by ice and water conjointly (stratified, but stratification more or less disturbed), and (3) those made by water emanating from the ice (stratified; cross-bedding common).

*Ground moraine* (p. 159) is nearly co-extensive with the ice-sheets themselves, though it failed of deposition in some places, and has

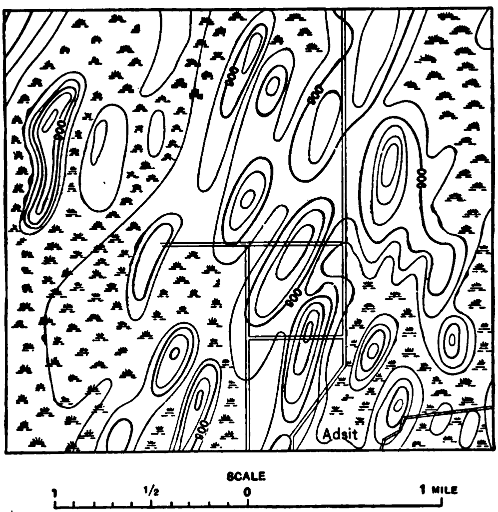



Fig. 519. One phase of ground moraine topography; elongated hills of drift of the type shown, are called *drumlins;* southeastern Wisconsin. (U. S. Geol. Surv.)

been removed in others. The ground moraine (*till*) of the North American ice-sheets is thickest in a broad belt a little within the margin of the drift (Fig. 504), extending from central New York through Ohio, Indiana, Illinois, Iowa, Minnesota, and the Dakotas, and thence northwestward. The topography of the ground moraine varies within wide limits. It is commonly undulatory, involving gentle swells and sags. In some places the swells take on rather definite elongate shapes, with their longer axes in the direction of ice movement. They are then called *drumlins* (Fig. 519). Drumlins have pronounced development in eastern Wisconsin, where they are numbered by the thousand, in central and western New York,

[1] Jour. Geol., Vol. II, pp. 517–538, and Internat. Geol. Congr., 1893.

in some parts of New England, and in some other places. The drumlins of New York are, in general, longer and narrower than those of Wisconsin.

The origin of drumlins has been much much discussed. Opinion is divided chiefly between the views (1) that they were accumulated beneath the ice under special conditions, and (2) that they were developed by the erosion (by the ice) of earlier aggregations of drift.[1]

A *terminal moraine* (p. 149) may be very like the adjacent ground moraine in constitution, though in many places there is more strati-

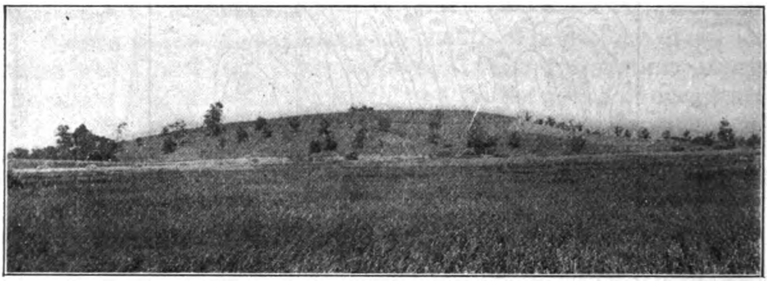


Fig. 520. A Wisconsin drumlin seen from the side; two miles north of Sullivan. (Alden, U. S. Geol. Surv.)

fied drift associated with it. It commonly constitutes something of a ridge, but it is more accurately characterized as a belt of thick drift. Its most distinctive feature does not lie in its importance as a topographic feature, but in the details of its own topography. Its surface is, as a rule, characterized by hillocks and hollows, or by interrupted ridges and troughs (Figs. 168 and 514). Many of the hollows and troughs contain marshes, ponds, and lakes. The shape and abundance of round and roundish hills, and of short and more or less serpentine ridges closely huddled together, have given rise locally to such descriptive names as "knobs," "short hills," etc.; but it is the association of "knobs" or "short hills"

[1] Some of the more important papers on drumlins are: Upham, Proc. Bos. Soc. Nat. Hist., 1879, pp. 220–234, ibid., Vol. XXIV (1889), pp. 228–242; Chamberlin, Third Ann. Rept., U. S. Geol. Surv., 1883, p. 306, and Jour. Geol., Vol. I, pp. 255–267; Davis, Am. Jour. Sci., Vol. XXVIII (1884), pp. 407–416; Salisbury, Glacial Geology of New Jersey, 1902; Lincoln, Am. Jour. Sci., Vol. XLIV (1892), pp. 293–296; Tyrrell, Bull. Geol. Soc. Am., Vol. I (1890), p. 402; Leverett, Monogrs. XXXVIII and XLI, U. S. Geol. Surv., and Russell, Amer. Geol., Vol. XXXV (1905), p. 177.

with "kettles," and not either feature alone, which is characteristic of terminal moraine topography.

The "knobs" vary in size, from low mounds but a few feet

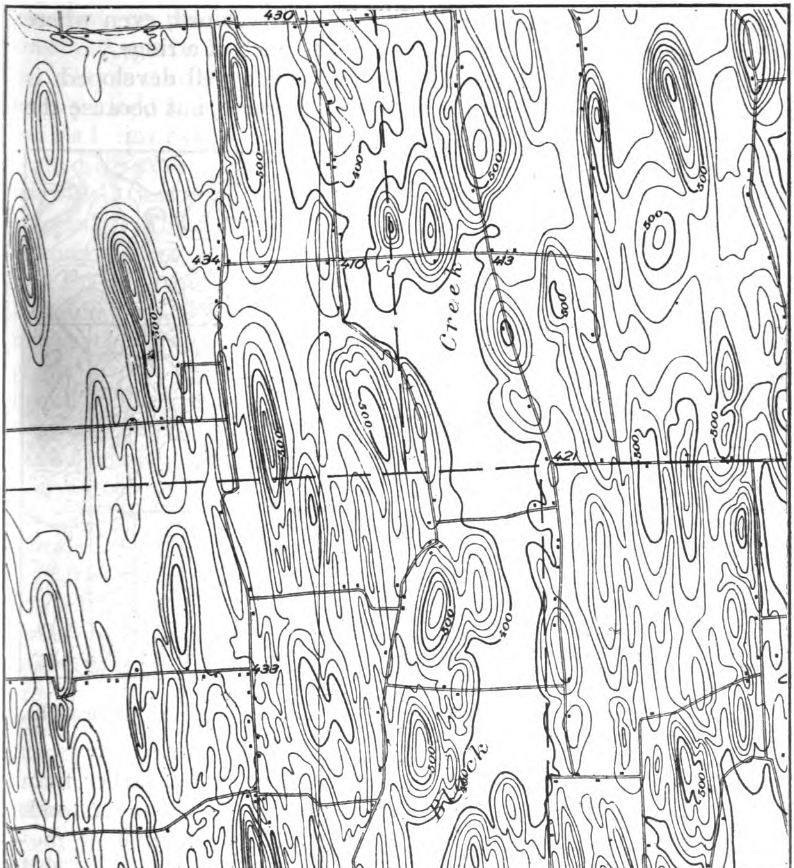



Fig. 521. Drumlins in contour, near Clyde, N. Y. (U. S. Geol. Surv.)

across, to hills half a mile or more in diameter, and a hundred feet or more in height. Not rarely they are about as steep as the material of which they are composed will lie. The "kettles" are the counterparts of the elevations. They may be a few feet, or many

rods, or even furlongs in diameter. They may be so shallow that the sagging at the center is hardly seen, or they may be scores of feet in depth. Where steep-sided depressions are closely associated with abrupt hillocks, the topography is notably rough. The topography of the terminal moraine may be well developed, even where the moraine as a whole does not constitute much of a ridge.[1]

The surface of the terminal moraine, where well developed, is generally rougher than that of the ground moraine, but because the

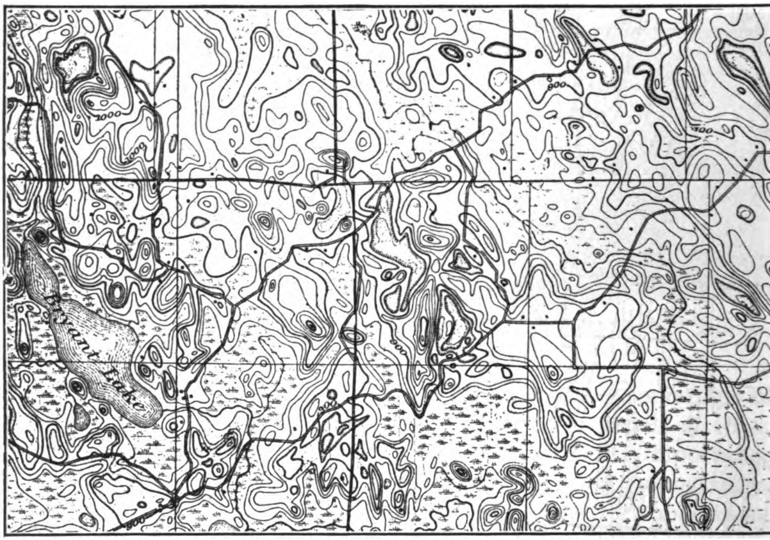



Fig. 522. Topography of drift shown in contours; an area near Minneapolis, Minn. Scale about one inch to the mile. (U. S. Geol. Surv.)

sags and swells are of smaller area and steeper slopes, rather than because the relief is notably more. It is not to be understood, however, that the topography described affects all terminal moraines, or that it is confined strictly to them. The elevations and depressions of terminal moraines grade from strength to weakness, and locally even disappear, while the features characteristic of terminal moraines are found, now and then, in other parts of the drift.

[1] References to papers on terminal moraines: Chamberlin, Third Ann. Rept., U. S. Geol. Surv., 1881–2, pp. 291–402, and Amer. Jour. Sci., Vol. XXIV (1882), pp. 93–97; Salisbury, Glacial Geology of New Jersey, pp. 92–100 and 231–260.

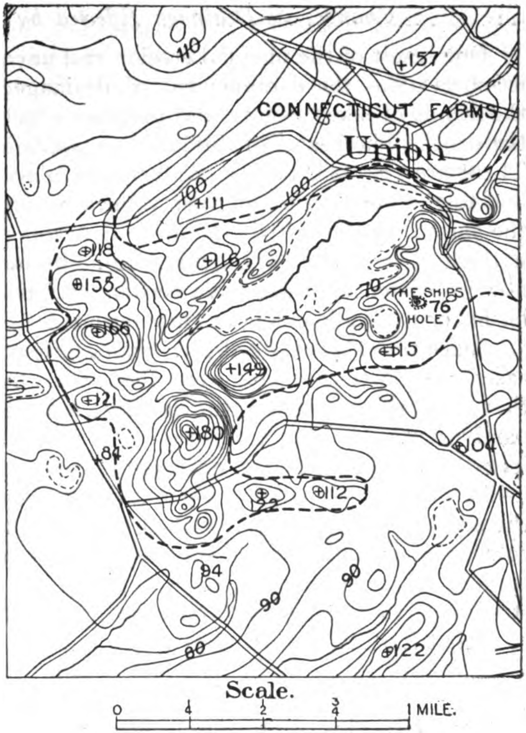



Fig. 523. A group of kames near Connecticut Farms, N. J. (N. J. Geol. Surv.)

Where an ice-sheet halted in its retreat, its edge remaining in a constant or nearly constant position for a sufficiently long period, a terminal moraine (called a *recessional moraine*) was developed. The not uncommon impression that a terminal moraine necessarily marks the *terminus of the drift* is erroneous. The word *terminal* refers to the terminus of the ice at the time when it formed the moraine.

*Fluvio-glacial deposits* have been referred to in earlier pages (p. 164). They are made (1) at the edge of the ice (kames and various ill-defined accumulations of gravel and sand); (2) beyond the edge of the ice (valley trains,

Fig. 524. Diagram to illustrate kame terraces. *ABC* represents the stratified drift of the kame terraces which are underlain by ground moraine. Till also covers the valley bottom.

outwash plains, deltas and various ill-defined bodies of stratified drift); and beneath the ice (eskers, etc.).

### *Changes in Drainage Effected by Glaciation*

One result of the unequal erosion and unequal deposition by the ice-sheets was the derangement of drainage. This is seen in the thousands of lakes, ponds, and marshes which affect the surface of the drift. The basins of the lakes or ponds arose in various ways. There are (1) rock basins produced by glacial erosion; (2) basins due to the obstruction of river valleys by drift; (3) depressions in the surface of the drift itself; and (4) basins produced by a combination of two or more of the foregoing. Besides the lakes and ponds now in existence, others have become extinct by the filling of their basins or by the lowering of their outlets.

Glaciation also changed the courses of many streams. In many cases, pre-existing valleys were filled with drift in some places, so that when the ice melted, the drainage followed courses which were partly new. In other cases, the ice forced streams to flow around its edge, and some of the drainage channels thus established were held after the ice melted. There are few streams of great length in the area covered by the ice which were not turned from their old courses for greater or less distances by the ice or the drift which the ice left. The Mississippi, the Ohio, and the Missouri, the master streams of the United States within the glaciated area, and a host of their tributaries, suffered in this way.[1]

### *Succession of Ice Invasions*

The glaciation of North America was accomplished by a series of ice-sheets separated from one another by long intervals of time. Some of the interglacial intervals were much longer than the time since the last ice-sheet disappeared, and there is also good evidence that in some of them the climate was at least as mild as to-day.

The proofs of the interglacial intervals and the evidences of

[1] For changes in the Mississippi and in the rivers of Illinois, see Leverett, Monogr. XXXIII, U. S. Geol. Surv., p. 120. For changes in the Upper Ohio, see Chamberlin and Leverett, Am. Jour. Sci., Vol. XLVII, 1894 (contains references to earlier work in this region). For changes in the Erie and Ohio Basin, see Leverett, Monogr. XLI, U. S. Geol. Surv., Chap. III, and Tight, Professional Paper No. 13, U. S. Geol. Surv. For changes in the course of the Upper Missouri and its tributaries, see Todd, Science, Vol. XIX, p. 148 (1892), Geol. of S. Dak., pp. 128 and 130 (1899), and Bull. 144, U. S. Geol. Surv. Changes in drainage in New York have been summarized by Tarr, Phys. Geog. of New York, 1902, with references to earlier literature.

their duration are found (1) in the erosion effected by streams after the deposition of one sheet of drift and before the deposition of the next, (2) in the depths to which earlier sheets of drift were leached and oxidized by weathering before the deposition of later ones upon them, (3) in the accumulations of peat, soil, etc., now found between different sheets of drift, and (4) in the changes of topographic attitude which intervened between the deployment of successive ice-sheets.[1]

The following are the stages of the glacial period recognized in North America numbered in the order of their age:

VIII. The Glacio-lacustrine (including the Champlain).
VII. The Wisconsin or Wisconian, the last important invasion.
VI. The Sangamon-Peorian, or third interglacial interval.
{VB. The Iowan, the third invasion in the Keewatin field.
{VA. The Illinoian, the third invasion from the Labradorean field.
IV. The Yarmouth or Buchanan,[2] the second interglacial interval.
III. The Kansan, or second ice invasion.
II. The Aftonian, or first interglacial interval.
I. The Jerseyan or sub-Aftonian ice invasion, the earliest recognized.

I. **Jerseyan or Sub-Aftonian glacial stage.** The oldest drift which appears in New Jersey is but the frayed edge of a once continuous sheet, and is very old. On the Allegheny and upper Ohio rivers, the great age of the oldest drift is shown by the deep erosion of the valleys since the first ice invasion turned the streams into new channels. Farther westward the corresponding old drift is covered by later drift. In the Keewatin area in Iowa, a very old drift (sub-Aftonian), probably the equivalent of the Jerseyan, lies below the Aftonian and Kansan. Very old mountain drift has recently been found (Atwood) high on the mesas near the San Juan Mountains in Colorado and also on the high mesas in front of the Rocky Mountains in Montana (Alden). The evidences of age of all these seem to be of the same order, and they are thought to represent the earliest ice invasions in the Labradorean, Keewatin, and Cordilleran fields.

II. **Aftonian interglacial interval.** Overlying the oldest till in

[1] Distinct glacial epochs and criteria for their recognition, Jour. Geol., Vol. I, pp. 61-84.

[2] The Buchanan gravels lie between the Kansan and Iowan drift-sheets where the Illinoian is not present, and hence their age is not quite certain.

Iowa is an irregular sheet of sand and gravel with remnants of old soil, muck, and peat, with stumps and branches of trees. The surface of the drift beneath shows much weathering and erosion. The fossils in these interglacial beds imply a cool-temperate climate; but as a cool-temperate stage must be passed through twice between successive glacial epochs, once as the ice retreats, and a second time as it advances again, fossils indicating a cool climate do not necessarily show how warm the interglacial epoch may have become.

III. **Kansan glacial stage.** The Kansan stage is represented by a sheet of till occupying a large surface area in Kansas, Missouri, Iowa, and Nebraska. Theoretically it extends under the later glacial formations to the northward, as far back as the Keewatin center of radiation. Much of this sheet of drift, as originally developed, probably was rubbed away by later glaciations. Presumably a similar sheet was formed by a contemporaneous ice-sheet spreading from the Labrador center, but it has not been certainly identified. The Kansan till is clayey and there is little stratified drift associated with it.

IV. **The Yarmouth interglacial stage.**[1] Where the Illinois till overlaps the Kansan (eastern Iowa), an old soil, with deep subsoil weathering, lies on the surface of the latter.

V. **Illinoian and Iowan glacial stages or Iowa-Illinoian stage.** On the borders of the Labradorean field near the Mississippi River, the Illinoian drift sheet overlies the Kansan sheet with the Yarmouth beds between. In the Keewatin field in eastern Iowa, the Iowan drift lies over the Kansan, with the Buchanan beds between. Some geologists now think that the Iowan represents the same stage in the Keewatin field that the Illinoian does in the Labradorean field; i. e., the third ice invasion. The earlier view was that the Illinoian drift was the older.

V. A. **Illinoian drift sheet (Labradorean field).** The exposed portion of this drift occupies the surface in the southern and western parts of Illinois. It runs back under the later drift to the northeast toward the Labradorean center. To the eastward, it is traced as far as Ohio, where it is covered by later drift. To the northward its margin is covered in southern Wisconsin, but in central Wisconsin it seems to re-appear and is traced westward on the north side of the driftless area, beyond which, in Minnesota, it seems to connect with the Iowan drift. The Illinoian till is clayey, with little

[1] Leverett, Mono. XXXVIII, U. S. Geol. Surv.

assorted drift associated. The west edge of the Illinoian ice-lobe pushed out into Iowa a score of miles, forcing the Mississippi in front of it. Ice of the Kansan epoch had earlier invaded Illinois from the west, and probably forced the Mississippi east of its present course, if such an easterly course had not been taken before the Kansan epoch.

V. B. **The Iowan drift (Keewatin field).** In northeastern Iowa the ice of this stage left a thin sheet of till marked by a profusion of large granitoid bowlders most of which lie on the surface. To the northward in Minnesota these bowlders are less abundant, and the formation passes beneath later drift. To the northeast it appears to be connected with the third drift of Wisconsin.

VI. **Sangamon interglacial stage.** In central Illinois a sheet of sandy material marked by remnants of old soil, muck, peat, weathering and erosion overlies the Illinoian glacial drift. Above this lies a mantle of loess and the Peorian peaty beds. According to the older view, the Iowan was placed between the Sangamon and the Peorian, now regarded, tentatively, as equivalents.

VII. **Wisconsin or Wisconian stage.** The ice radiated from the Labradorean, Keewatin, Cordilleran, and from many mountain centers. It had probably done this at each of the preceding glacial stages, but the record is much obscured by erosion and concealment. The margin of the Wisconian ice was pronouncedly lobate, and the drift which it left is characterized by stout terminal moraines, numerous kames, eskers, drumlins, outwash aprons, valley trains, and other features distinctive of glacial action and glacio-fluvial coöperation. This drift-sheet, more than any of the others, bears the stamp of the great agency of the period. The distinctive topography of the various phases of this formation is in contrast with the relatively expressionless surfaces of the older sheets of drift. Part of this difference is due to the fact that the Wisconsin formation has been eroded less than the older drifts; but the larger part, apparently, is assignable to a stronger original expression.

Unlike the earlier sheets of drift, the Later Wisconsin drift was not overriden by later sheets of ice, and its original development is therefore better shown at the surface. It has nearly a score of concentric terminal moraines in some places. Some of them represent re-advances of the ice in the course of its general retreat, while others mark halts in the retreat sufficient to permit an exceptional accumulation of drift at the border of the ice.

Not all of these several sheets of drift have been seen in superposition, and the history sketched above is based on the relations of the sheets of drift at different points.[1] Theoretically, the several sheets of drift are imbricated as suggested by Fig. 525, but each sheet of drift is discontinuous beneath the overlying one, and this

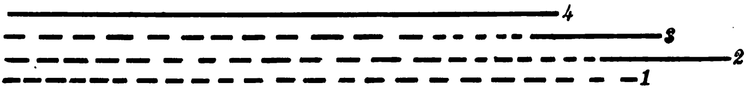



Fig. 525. Diagram illustrating the imbrication of the successive sheets of drift. The full lines represent the portion of the drift-sheets not overspread by later ice-sheets; the broken lines represent the portions of the successive drift-sheets which were covered by ice at a later time. 1 corresponds to Jerseyan or sub-Aftonian, which in general is less extensive than the Kansan, though locally, as in New Jersey, it extended farther south than any other; 2 represents the Kansan drift, the southern margin of which is not covered by younger drift; 3 and 4, respectively, represent the Illinois-Iowan, and Wisconsin sheets of drift.

discontinuity goes so far that beneath the Wisconsin drift, for example, the several sheets are more commonly wanting than present.

VIII. **Glacio-lacustrine stage.** In the course of the retreat of the ice of the Wisconsin epoch, a complex series of lakes arose between the ice border on the one hand, and the higher land fronting it on the other. Many of these lakes were temporary and shifting, and had shifting outlets. Their history cannot be given here; but a brief sketch of the history of the Great Lakes will indicate the nature of the changes which took place.

When the end of the Lake Michigan ice-lobe (Fig. 526) withdrew a little from the southern end of the Lake Michigan basin, a lake formed there, and discharged its waters into the Illinois valley southwest of Chicago. The channel followed by the outflowing waters has since become the site of the Chicago drainage canal. The glacial lake (Lake Chicago) thus initiated was gradually extended northward (Fig. 527) as the ice-lobe was melted.

A similar lake was formed about the head of the Lake Superior ice-lobe. Lake Maumee developed about the end of the Erie ice-lobe, and its waters flowed to the Wabash. A later stage of Lake Chicago and Lake Maumee is shown in Fig. 527, when, finding a lower outlet as the ice melted back, Lake Maumee sent its outflow across southern Michigan to Lake Chicago.

Later, the whole Erie basin, and a portion of that of Ontario,

[1] Jour. Geol., Vol. I, pp. 61–84.

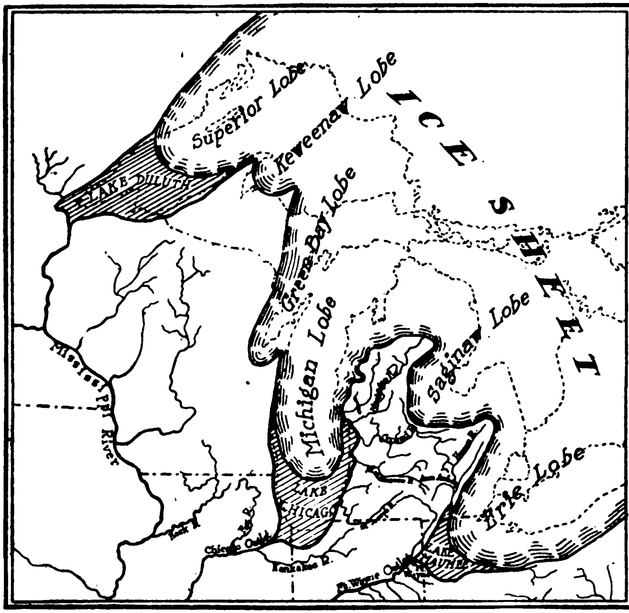



Fig. 526. The beginning of the Great Lakes. The ice still occupied the larger parts of the present lake basins. (U. S. Geol. Surv.)

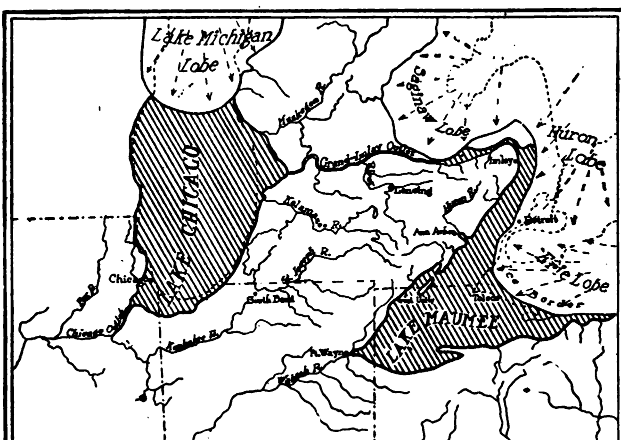



Fig. 527. A later stage in the development of Lakes Chicago and Maumee. The ice has retreated, and the outlet of Lake Maumee has been shifted. (U. S. Geol. Surv.)

was freed of ice, and a lake (Lake Arkona) twice as large as Lake Erie developed. An advance of the ice changed the lake and with its changed outline it is known as Lake Whittlesey (Fig. 528.)


Fig. 528. A later stage in the development of Lakes Chicago, Maumee, and Saginaw. (Leverett and Taylor, U. S. Geol. Surv.)

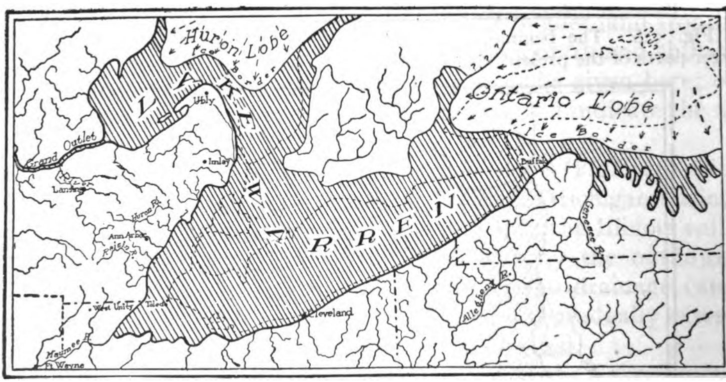



Fig. 529. Illustrating the relations of standing water to the ice in the Erie and Ontario regions after the ice had retreated farther than represented in Fig. 528, The numerous lobate arms of lakes south of the Ontario lobe of ice will be noted, and also the fact that the discharge of Lake Warren was still to Lake Chicago. (Taylor and Leverett, U. S. Geol. Surv.)

With further retreat of the ice, the ponded waters of the region assumed the form shown in Fig. 529. At first, this lake discharged across Michigan into Lake Chicago, but later, when the Mohawk

valley was freed from ice, it offered the lower outlet, and the level of Lake Warren was drawn down, and it was divided into two lakes, Erie and Iroquois (Fig. 530).

Meantime, the glacial lakes in the basins of Lakes Michigan and Superior experienced analogous shiftings of areas and of outlets. While Lake Iroquois was discharging through the Mohawk valley, Lake Algonquin (Fig. 530), was discharging its waters eastward. At first the outlet was probably by the St. Clair-Erie route, through

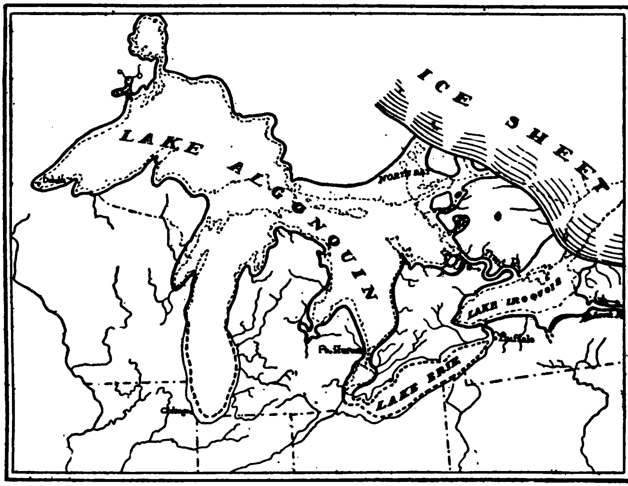



Fig. 530. The Great Lakes at the Algonquin-Iroquois stage. The outlet to the sea is by way of the Mohawk Valley. (Taylor.)

Lake Iroquois, to the Mohawk; but later, when the ice had retired farther north, an outlet appears to have been opened from Georgian Bay to Lake Iroquois, by way of the Trent River.

When at length the ice withdrew from the Adirondacks so far as to permit the waters of Lake Iroquois to find an outlet lower than that by way of the Mohawk, a new series of lowerings of the lakes followed. At first the outlet seems to have skirted the Adirondacks and emptied into a glacially-ponded water-body (glacial Lake Champlain) which occupied the Champlain basin, and discharged southward through the Hudson. Later Lake Algonquin gave place to the great Nipissing Lakes (Fig. 531), which had their outlet via Lake Nipissing to the Ottawa, and thence to the Champlain arm of

the sea. Subsequently the outlet was shifted to its present position, probably by a gentle upwarping of the surface at the north.

Similar complicated histories doubtless attended the retreat of the ice in the Mackenzie and Hudson Bay basins, but little is yet known regarding them. A very important lake was formed in the Red River valley of the North (Lake Agassiz, Fig. 532), discharging,

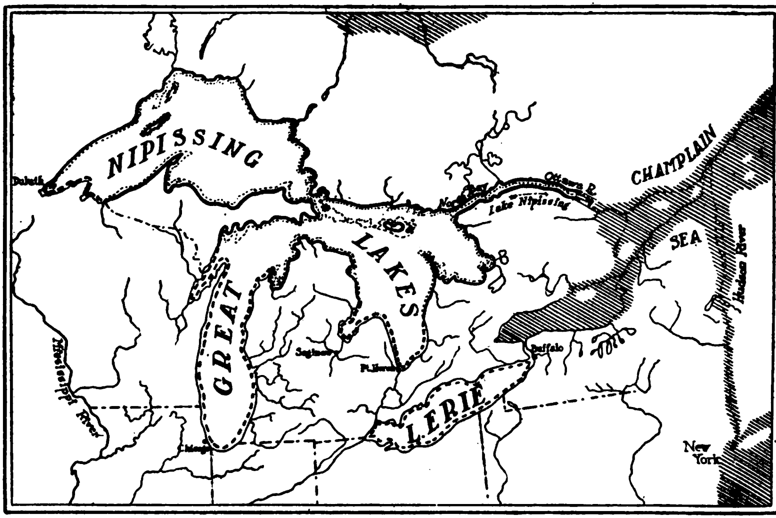



Fig. 531. A still later stage of the Great Lakes. The sea is thought to have covered the area shaded by lines at the east. (Taylor.)

in its earlier history, into the Minnesota River at Lake Traverse. Lake Agassiz had a comparatively simple history. It grew to the northward with the retreat of the ice which held it in at that end, and continued to discharge into the Minnesota River until the retreat of the ice gave it a northerly outlet. It developed beaches while it discharged to the southward, and another set after the outlet was northward. On the final withdrawal of the ice, the lake was drained.

The evidence which demonstrates the existence of these expanded lakes is found chiefly in the deposits which they made, and in the topographic features which they developed about their shores. Many of the former shore-lines have been traced in detail, and most of them depart notably from horizontality. In general, they rise

to the north and northeast. It is probable that there were corresponding lacustrine substages at the close of each of the several glacial epochs, but their history is not known.

In the later part of this substage, an arm of the sea extended up the St. Lawrence to Lake Ontario, filling the basin of Lake Champlain (Fig. 531). It probably connected southward by a narrow

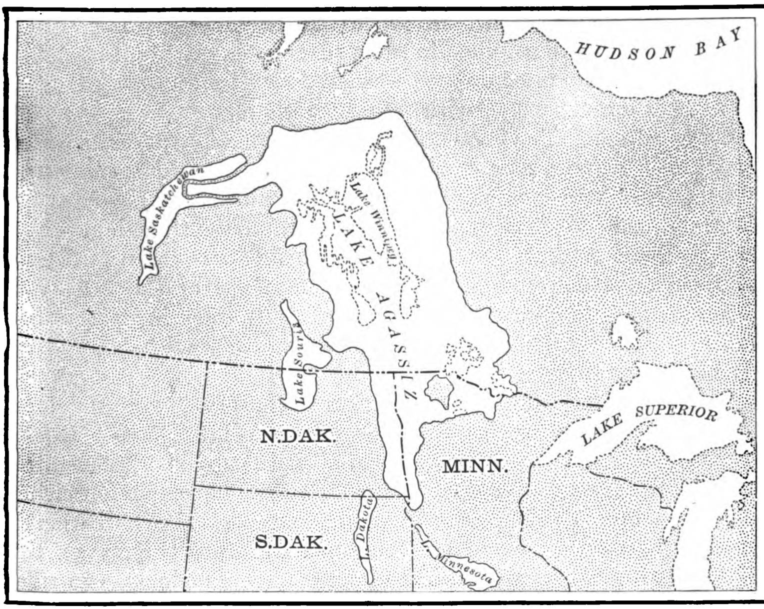



Fig. 532. Map of the extinct Lake Agassiz, and other glacial lakes. Lake Winnipeg occupies a part of the basin of Lake Agassiz. (U. S. Geol. Surv.)

strait along the site of the Hudson valley with the ocean. The sediments deposited in this arm of the sea contain shells and bones of marine animals. The marine fossils are found at various places about Lake Champlain at altitudes varying from 400 feet or less about the south end of the lake, to 500 feet at the north end, and about 600 feet near the east end of Lake Ontario.[1] At about the same time the sea stood higher than now relative to the land on the

[1] Dawson, G. M., Am. Jour. Sci., 3d ser., Vol. VIII (1874), p. 143; Dawson, J. W., The Canadian Ice Age, p. 201, and Am. Jour. Sci., Vol. CXXV, 1883.

coast of Maine, where marine shells occur up to elevations of 200 feet or more,[1] and to still greater heights farther north.

### *Loess*

The term loess is used both as a textural and a formational name. Lithologically, it is a silt intermediate between sand and clay. It is generally free from stones of all sorts except concretions developed in it since its deposition. In the exceptional cases where stones occur in it, they are confined in most cases to its very bottom, or to loess which has slumped or been washed down from its original position. It is interstratified with sand in some places.

**Composition.** The loess contains many angular, undecomposed particles of the commoner carbonates (calcite and dolomite) and silicates (feldspars, amphiboles, pyroxenes, micas, etc.), and a few of the rarer silicates. Magnetite also is a common, though never an abundant, constituent. All these are subordinate to quartz. These constituents strongly suggest that the material of the loess was derived from the rock-flour of the drift. In color it is generally buffish, but in not a few places it has a grayish (bluish) cast a few feet below the surface.

Loess stands readily with vertical faces (Fig. 533) for long periods, where sand or clay would be degraded into slopes. Roads on the loess tend to assume the form of little canyons, because the silt of the road-bed is washed or blown away, while that on either side stands up with steep or even vertical slopes. Many weathered faces of the loess show a rude columnar structure (Fig. 533), the columns being one to several feet in diameter. The loess, as a rule, shows no stratification, but in its coarser phases there is some suggestion of such structure, and where interbedded with sand, stratification may be distinct.

**Distribution.** The best known loess in America and Europe is associated with glacial drift, though loess extends far beyond the borders of the drift in some directions, in both continents. In China and other lands of Asia, where loess has great development, it is not generally associated with glacial formations.

In North America the loess does not occur east of the Mississippi basin, and has little development east of the Wabash River. It is widespread in Illinois and the states along the Missouri, and in

[1] Stone, Jour. Geol., Vol. I, pp. 246–254, and Bastin, Rockland, Me., folio, U. S. Geol. Surv.

the states along the Mississippi farther south. Within this area, its distribution is peculiar in that it follows the main streams, and is found especially on the bluffs overlooking the valleys. On this account it was formerly known as the *Bluff* formation. In this bluff-position, it has more than its average thickness and coarseness

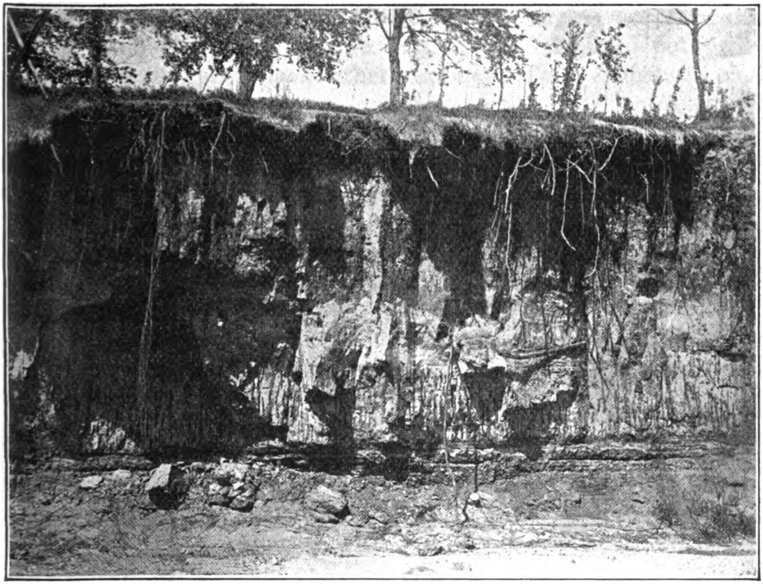


Fig. 533. A section of loess in Iowa, showing its ability to stand with vertical or even overhanging faces. (Calvin.)

of grain. It grows thinner and finer in grain back from the river bluffs, until it is lost in a vanishing edge. As it thins, its material loses its distinctive characteristics.

South of the borders of the Illinois-Iowan and Wisconsin drift-sheets, it mantles many of the divides between the main streams; but farther south it is confined more to the valley borders. Within the drift-covered part of the Mississippi basin, it occurs (1) as a surface mantle overlying drift, and (2) between sheets of drift. South of the drift there are in places (e.g. southern Illinois and northeastern Arkansas) two distinct sheets of loess, separated by a well developed soil zone. The surface of the lower sheet shows the effects of pro-

longed weathering and oxidation, in some places. Loess occurs in isolated spots even as far west as Washington and Oregon.

**Age.** The relations of the loess to the several drift-sheets make it clear that it was accumulated at different stages of the glacial

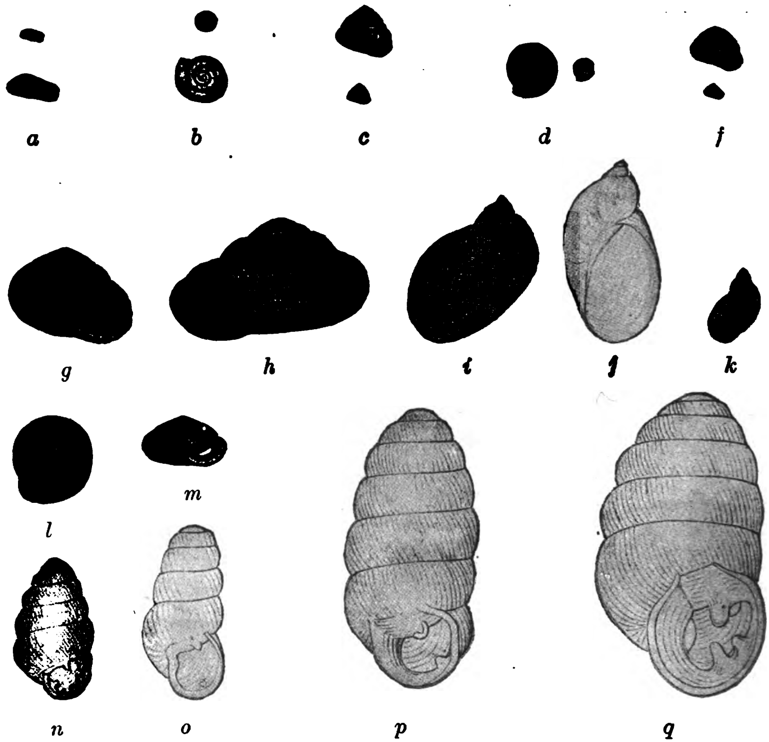



Fig. 534. *Loess Shells.* *a-b, Zonitoides minusculus* (Binney); *c-d, Euconulus fulvus* (Drap.); *e-f, Strobilops labyrinthica* (Say); *g, Polygyra clausa* (Say); *h, P. multilineata* (Say); *i-j, Succinea obliqua* Say; *k, S. avara* Say; *l-m, Polygyra monodon* (Rack); *n, Bifidaria pentodon* (Say); *o, B. corticaria* (Say); *p, B. muscorum* (Linn.); *q, B. armifera* (Say). The small figures adjacent to some of the large ones show the natural size of the shells.

period, but within the glaciated area most of it is younger than the Illinoian sheet of drift which it mantles, and older than the Wisconian drift which overlies it. Locally, loess covers Wisconsin drift in a few places. No considerable body of loess older than the Illinois drift has been identified with certainty.

**Thickness.** The loess of the Mississippi basin rarely is more than a score or two feet thick, and this only along the main valleys; but exceptionally its thickness approaches 100 feet. Thicknesses of 10 feet are much more common than greater ones.

**Accessories.** The loess contains characteristic accessories of two kinds, concretions and fossils. The concretions are of lime carbonate and iron oxide. Many of the former are irregular, and of such shapes as to have been called "petrified potatoes"; but many of them have other shapes. The ferruginous concretions take various forms, one of which is the "pipe stem," perhaps formed about rootlets. The fossils are chiefly gastropods (Fig. 534), almost wholly of land species, or of such as frequent isolated ponds. The other fossils are bones and teeth of land mammals.

**Origin.** There has been much diversity of opinion as to the origin of loess, the fundamental question being whether it is aqueous or eolian. There is little doubt that the loess-like silts which occur in the terraces of rivers are of fluvial origin; but some would not regard them as loess. Some, indeed, would restrict the term to an eolian product.

There is a growing conviction that most of the loess on the uplands, in the United States at least, is eolian. The river flats are supposed to have supplied much of the material of the loess, the alluvial silt being whipped up by the winds and re-deposited on the adjacent uplands. The rivers are thus made essential factors in its distribution, though not the direct agents of deposition. This hypothesis seems on the whole best to fit the phenomena of the larger part of the upland loess of the Mississippi basin. The constituents of the loess, which appear to have come from the glacial drift, were derived largely from the deposits made by glacial waters, or from later flood plain silts derived from the glacial formations; but it is probable that some of the loess was derived from glacial drift directly, before it became clothed with vegetation.[1]

[1] *References.* Loess is described in the geological reports of many of the states of the central Mississippi basin. Other references are McGee, Eleventh Ann. Rept., U. S. Geol. Surv.; Chamberlin and Salisbury, Sixth Ann. Rept., U. S. Geol. Surv.; Shimek, Am. Geol., Vols. XXVIII and XXX, Bull. Ia. Lab. Nat. Hist., Vols. I, II, and V, Proc. Ia. Acad. Sci., Vols. III, V, VI, and VII; Leverett, Am. Geol., Vol. XXXIII, and Monog. XXXVIII; Calvin, Bull. Geol. Soc. Am., Vol. X, p. 119; Chamberlin, Jour. Geol., Vol. V, 1897; Davis, *Explorations in Turkestan*, 1905; and Willis, *Researches in China*, Vol. I, Carnegie Institution.

### *Duration of the Glacial Period*

The desire to measure the great events of geological history in terms of years increases as our own time is approached. The uncertainties attending such measurements are, however, so great that the results have an uncertain value, and do little more than indicate the order of magnitude of the time involved. Attempts have been made (1) to estimate the relative duration of the several glacial and interglacial epochs, and (2) to estimate in years the time since the close of the glacial period.

1. The best data for estimating the relative duration of the several glacial stages are found in the central basin of the Mississippi, for here only are all members of the drift series present. The criteria that have been used in estimating relative duration embrace (1) the amount of erosion of the several drift sheets, (2) the depth of leaching, weathering, and decomposition of its materials, (3) the amount of vegetable growth in interglacial intervals, (4) the climatic changes indicated by interglacial and glacial floras and faunas, (5) the time needful for the migration of faunas and floras, particularly certain plants whose means of migration are very limited, (6) the time required for advances and retreats of the ice, and some others. A few of these, as the first, are subject to direct measurement; but most of them are matters of judgment. By the use of these data, it has been estimated that the time since the Kansan drift was deposited is some 15 to 20 times as long as the time since the last glacial epoch.

2. Of the efforts that have been made to measure in years post-glacial time, those based on the recession of Niagara and St. Anthony Falls are the most significant.[1] In both these instances, the measurement attempted is the time occupied in the recession of the falls from their starting point to their present positions.

If the length of the Niagara gorge be divided by the average annual retreat since the falls were first located by accurate surveys,

[1] *References on Niagara:* Gilbert, Am. Jour. Sci., 3d ser., Vol. XXXII, 1886; Science, Vol. VIII, 1886; Chapter in Physiography of the United States, and Bull. U. S. Geol. Surv. Upham, Am. Jour. Sci., 3d ser., Vol. XLV; Jour. Geol., Vol. I, 1893; Am. Geol., Vol. XI, 1893, and XVIII, 1896, and Pop. Sci. Mo., Vol. XLIX, 1896. Spencer, *Evolution of the Falls of Niagara;* Taylor, Bull. Geol. Soc. Am., Vol. IX, p. 84, and Vol. XXIV.

*St. Anthony Falls:* Winchell, N. H. Fifth Ann. Rept. Natl. Hist. and Geol. Surv. of Minn., 1876; Geol. of Minn., Vol. II, 1888, 23d Ann. Rept., 1894; Southall, The Epoch of the Mammoth, p. 373.

the quotient is about 7,000, but it is not safe to assume that this number of years is the time since the last glacial epoch. At the beginning of the cutting of the gorge, the waters of the upper lakes flowed by a more northerly route to the sea (Figs. 530 and 531), leaving only the waters of the Erie basin to pass over the falls. If the history is correctly read, it was at a comparatively late date that the waters of the Upper Great Lakes went out through the Niagara River. The early cutting was therefore much slower than the later. In view of these considerations, it is thought that 7,000 should be multiplied several times to give the true time-estimate. Spencer places the period at about 39,000 years, and Taylor at about 25,000 years.

It is to be noted that cutting of the *Niagara Gorge* could not have begun until the Mohawk outlet of the lakes (p. 639) was abandoned, and that the time measured by the Niagara cutting is only that which has elapsed since the ice melted back from the Adirondacks far enough to permit the waters of the ancestral Lake Ontario to find an outlet lower than the Niagara escarpment, and no very effective cutting could take place until the waters were withdrawn to something near their present level.

If the border of the ice-sheet at this stage (Fig. 531) is compared with the border of the ice at the maximum Wisconsin stage, it will be seen that it had retreated some 600 miles. The rate of recession of the ice is unknown, but 200 feet per year is an improbably high rate; but at this rate, the ice must have been receding some 15,000 years, before the falls came into existence. If this be added to the time occupied in the development of the gorge, say 25,000 to 40,000 years (estimated), the result is 40,000 to 55,000 years since the beginning of the retreat of the last great ice-sheet.

From a comparison of the earlier and later surveys of St. Anthony Falls, the time of recession of the falls from the mouth of the gorge has been estimated at about 8,000 years. But considerations not taken into account in this estimate make it clear that this estimate should be increased to 12,000 or 15,000 at least. If to these figures 20,000 years be added for the time of retreat (700 or 800 miles) before the falls began to develop, we have a total of more than 30,000 years since the climax of glaciation in the late Wisconsin epoch.

Little value is to be placed on estimates of this kind, except as means for developing a conception of the order of magnitude of the time involved.

### *Foreign*

In Europe, the succession of ice epochs and formations is not less complex than in North America, though there is not complete agree-

ment among geologists as to the number of glacial epochs.[1] In the Alps four are recognized.[2] These are designated[3] Günz (pre-Kansan?), Mindel (Kansan?), Riss (Iowa-Illinoian), and Würm (Wisconsin?). The glacial formations of other continents have not been studied in detail in many places, but recent studies in Turkestan indicate that there were several glacial epochs in the Thian Shan Mountains.[4]

### CAUSE OF GLACIAL CLIMATE

Many hypotheses of the cause of the glacial period have been offered, but none commands universal assent. Most of them appeal to a combination of agencies, but each centers on some one factor which gives character to the hypothesis. They fall mainly into three classes: (1) those based on elevation of the land, the *hypsometric hypotheses;* (2) those based on phenomena and relations outside the earth itself, the *astronomic hypotheses*, and (3) those based on changes in the constitution, movements, or cloud-content of the air, the *atmospheric hypotheses.*

**Hypothesis of elevation.**[5] Since the best-known glaciers are in mountains, the suggestion was natural that elevation of the glaciated regions was the cause of the great ice-sheets. The chief evidence of the elevation postulated is the submerged valleys of the sea-coasts, especially those of the northern latitudes. It has been held by advocates of this hypothesis that 4,000 feet or more of elevation is indicated by the northern fiords, and that this elevation, together with accompanying geographic changes, was competent to produce the Pleistocene glaciation. Those who question this view doubt the fact of so great elevation, and doubt whether any elevation which there may have been was contemporaneous with the ice-sheets. Further, they offer evidence that the land was lower than now at certain important stages of the glacial period. The elevation hypothesis also encounters grave difficulty in explaining the repetition of glacial epochs and interglacial epochs, and in accounting for the mild climates of interglacial times. In its simple

[1] Geikie, Jour. Geol., Vol. III, pp. 241–269. Keilhack, ibid., vol. III, pp. 113–125.

[2] Penck, Die Alpen im Eiszeitalter.

[3] Penck, Science, Vol. XXIX, p. 359.

[4] Huntington, Explorations in Turkestan, Carnegie Institution.

[5] Dana, Manual of Geology, 4th ed., p. 970, and Upham, Am. Geol., Vol. VI, p. 327, and Am. Jour. Sci., Vol. XII, p. 33.

and popular form, the hypothesis would seem to require a great elevation of a large part of two continents for each ice epoch, and a great depression for each interglacial epoch, an extremely improbable sequence of events. This hypothesis has lost rather than gained favor, as evidence has accumulated.

**Astronomic hypotheses.** An ingenious semi-astronomical hypothesis was advanced by Croll[1] in the latter part of the last century, and for a time it was widely accepted. It is founded primarily on variations in the eccentricity of the earth's orbit, combined with the precession of the equinoxes. Plausible as the hypothesis seemed at the outset, prolonged study has tended to weaken, rather than strengthen it.

The orbit of the earth is slightly elliptical, and this ellipticity is subject to considerable variation. This does not alter the total amount of heat received from the sun by the earth, or by either hemisphere; but it affects the *distribution* of heat within the year, shortening or lengthening the cooler and warmer seasons, according as they fall in the perihelion or the aphelion part of the earth's orbit. Thus the hemisphere which has summer in perihelion has a short summer with much heat per hour; the other hemisphere has a long summer with less heat per hour. The precession of the equinoxes reverses the seasonal relations of the hemispheres every 10,500 years. At present the earth is nearest the sun in winter in the northern hemisphere (summer in the southern hemisphere). In 10,500 years (owing to the precession of the equinoxes) the earth will be nearest the sun in the summer of the northern hemisphere (winter of the southern hemisphere). We shall then have a shorter summer with more solar heat per hour than now, and a longer winter with less heat per hour. Croll's hypothesis is built upon the belief that snow-accumulation would be favored by long winters, and snow-melting reduced by short summers. The hypothesis is that the glacial epochs occurred during the period of aphelion winters in times of great eccentricity.

It is admitted that these astronomical relations are insufficient in themselves to produce the observed glaciation, and so certain terrestrial conditions were made important elements in the working force of the hypothesis. It was held that the zone of the trade-winds and the thermal equator would be shifted from the glaciated hemisphere toward the warmer one, and that this shifting would turn a large part of the warm equatorial waters away from the cooler hemisphere. Croll held that if the trade-wind belts were shifted southward a few degrees, a large part of the equatorial current would be south of Cape St. Roque, and so turned into the South Atlantic, greatly lowering the temperature of the northern hemisphere. When the southern hemisphere was passing through its cold period, nearly all the equatorial current would be north of St. Roque, and this would give the northern hemisphere a moist interglacial epoch.

If the hypothesis were correct, (1) glacial epochs should alternate between the northern and the southern hemispheres, and (2) their duration should be limited

[1] *Climate and Time in their Geological Relations;* James Croll, pp. 312–328; *Climate and Cosmology* and *The Cause of the Ice Age*, Sir Robt. Ball.

to an appropriate fraction of the precessional period. This appropriate fraction is probably about that which effective winter bears to the whole year. In the middle latitudes, the effective period of cold would perhaps be 5,000 or 6,000 years. These features of the hypothesis afford a means of testing it. If it be true, the glacial epochs should be of equal length; all of them should be short, and all of those in the same period of eccentricity, equally distant from each other in time. If the computed periods of eccentricity are correct, there could be only a few alternations of glaciation between the hemispheres within a given period of high eccentricity, and none of them could be more recent than 60,000 years. Croll placed the close of the glacial period 80,000 years ago.

The glacial studies of recent years seem to show that the intervals between the different invasions are of very unequal duration, and that the most recent is relatively young. It has also been found that glaciation was extended notably beyond its present limits on the lofty mountains of the equatorial regions, though climate there should not have been much affected. The Labradorean and Keewatin ice-sheets pushed out from what appear to have been their centers about 1,600 and 1,500 miles respectively. If one foot per day be allowed for the advance of the margin — an estimate much beyond the probabilities — it would take more than 20,000 years for the ice-edge to reach the extension observed. This is almost the whole of a precessional period. Nor is the difficulty escaped by assuming that the snow-field grew up simultaneously over the whole area, or some large part of it, for bowlders are found 600 to 1,000 miles from their probable sources. To allow time for the residue of winter snow above summer melting to build itself up to a height capable of giving effective motion, and then to allow time to carry drift this great distance at any probable rate of motion, taxes the hypothesis very severely, to say the least.

*Other astronomical hypotheses.* Attempts have been made to base other theories on the eccentricity of the earth's orbit, and also on variations in the obliquity of the ecliptic; but none of them has gained much acceptance. They encounter most of the difficulties of the Crollian hypothesis, in somewhat different forms. There have been speculations upon the possible passage of the earth through cold regions of space, but there is no astronomical basis for them.

It was early suggested that the axis of the earth may have been shifting its geographic position, and that the Pleistocene glaciations were but polar glaciations of the existing type, at a time when the north pole was 15° or 20° south of its present position. So long as the theory of a thin crust resting on a liquid nucleus, and capable of sliding over it, was accepted, the mechanical difficulties of this hypothesis did not seem insuperable; but if the earth is essentially rigid, as now seems certain, the dynamic objections to this hypothesis are fatal.

**Atmospheric hypotheses.** The leading hypothesis of the atmospheric class is based chiefly on a postulated variation in the constitution of the atmosphere, especially in its amount of carbon dioxide and water. Both these elements have high capacities for absorbing heat, and both are being supplied constantly and constantly consumed. Periods of great land elevation and extension are periods of great erosion and of great consumption of carbon dioxide, for under these conditions weathering is at a maximum, and carbon

dioxide from the air takes part in the decomposition of rock in a large way (p. 264). So also, at times of great land elevation and extension, the sum total of evaporation of water is reduced, and the average amount of water vapor in the air is correspondingly lowered. The great elevation of land at the close of the Tertiary seems to afford conditions favorable both for the consumption of carbon dioxide in large quantities, and for the reduction of the water content of the air. Depletion of these heat absorbing elements was equivalent to the thinning of the thermal blanket which they constitute. If it was thinned, the temperature was reduced, and this would further decrease the amount of water vapor held in the air. The effect would thus be cumulative. The elevation and extension of the land would also produce its own effects on the prevailing winds and in other ways, so that some of the features of the hypsometric hypothesis form a part of the atmospheric hypothesis. This hypothesis also takes into account the action of the ocean in absorbing and giving forth carbon dioxide under the varying conditions that prevailed. It is thus a highly complex hypothesis and cannot be set forth in detail here.[1] By variations in the consumption of carbon dioxide, especially in its absorption and escape from the ocean, the hypothesis attempts to explain the periodicity of glaciation.

While this hypothesis is still new and on trial, it is the only one which has been worked out into such detail as to fit the leading facts now developed by studies of the glacial formations. It should be understood, however, that its truth remains to be established, and that modifications and additions may yet be required.

Hypotheses have been based on the direction of the prevailing winds and also upon the degree of cloudiness; but these have not been satisfactorily connected with known causes and with the conditions prevailing in Pleistocene times. Furthermore, they have not been shown to fit the facts of periodicity and localization, facts which all hypotheses must meet before they can have serious claims to acceptance.

### FORMATIONS OUTSIDE THE ICE-SHEETS

While the glaciation of middle and high latitudes was the most striking event of the Quaternary period, by far the larger part of the earth's surface was not affected directly by the ice, and outside the area of the continental ice-sheet, the commoner phases of erosion

[1] For a fuller exposition of this hypothesis see Chamberlin and Salisbury's Earth History, Vol. III, pp. 432–446.

and deposition were in progress, and non-glacial Pleistocene formations are widespread. Under the varied conditions of the period, various classes of deposits were made, among which were the following: (1) *Eolian deposits*, conspicuous along many shores and rivers, and in sundry arid regions, and inconspicuous as dust over much larger areas. (2) *Fluviatile deposits*, made by streams (a) with, and (b) without, connection with the ice. These deposits occur along most streams of low gradient, and along many others. Kindred deposits were made by sheet-floods and temporary streams, even far from the courses of permanent streams. (3) *Lacustrine deposits* of both the glacial and non-glacial types, made in existing lakes and about their borders, and also over the sites of the numerous lakes which have become extinct since the beginning of the period. (4) *Deposits made by springs.* (5) *Terrestrial organic deposits* (peat, calcareous marl, etc.) occur outside the area directly affected by the ice, but are more common in the ponds and marshes to which glaciation gave rise. (6) *Marine deposits*, on lands submerged during the Pleistocene period, and doubtless over essentially all of the ocean bottom. (7) *Volcanic rocks* of Pleistocene age are found in our continent, chiefly west of the Rocky Mountains, though volcanic dust is distributed widely on the Great Plains. All these kinds of deposits were doubtless made at other periods, but have not been preserved so generally.

The average thickness of the Pleistocene deposits is not great. Pleistocene accumulations of debris at the bases of mountains are several hundreds of feet thick in some places; but otherwise the thickness of non-glacial Pleistocene deposits rarely exceeds a few score feet.

**Atlantic and Gulf coasts: Columbia series.** On the Coastal Plain of the Atlantic and the Gulf of Mexico, there is a widespread but thin body of gravel, sand, loam, and clay, referred to the Pleistocene period. It ranges from sea-level up to altitudes of several hundred feet, though most of it lies below 200 feet. All of the non-glacial post-Tertiary deposits of the Atlantic and Gulf plains were formerly grouped together under the name *Columbia;* but the materials formerly grouped under this name represent at least three somewhat distinct stages of deposition.[1]

The oldest subdivision of the Columbia series (*Qc*, Fig. 535) is

[1] Reports of the State Geologist of New Jersey, 1897–1900; also Philadelphia folio U. S. Geol. Surv.

found at levels higher than those of the younger subdivisions. In the principal valleys, it constitutes broad, mostly rude terraces, which rise up-stream. Up the Potomac, the Susquehanna, the


Fig. 535. Diagram showing the relations of the three divisions of the Pleistocene as seen in valleys. *Qc* = the high-level Columbia, *Qp* = the low-level Columbia (or Pensauken), and *Qcm*, the Cape May formation.

Delaware, and other valleys, the terraces rise to altitudes notably above those attained by the formation outside the valleys. In the District of Columbia, the second member of the Columbia series (*Qp*) covers rock terraces 100 feet or so below the oldest member phase of the series (Fig. 535). The relations of the two subdivisions indicate that extensive erosion followed the deposition of the first, and that the broad valleys then developed were subsequently aggraded by sediments similar to those of the preceding epoch of deposition. The two deposits are so nearly alike in composition that their separation is based chiefly on their topographic relations. The third phase of the composite Columbia is found at still lower levels along the streams and coasts. Its disposition is such as to show that the second phase of the Columbia formation had been extensively eroded before the deposition of the third. In the valleys formed during this interval of erosion, and along the coast at accordant levels, the third member of the series finds its chief development.

The various members of the Columbia series rest unconformably on older formations. On the Atlantic Coast, the oldest division

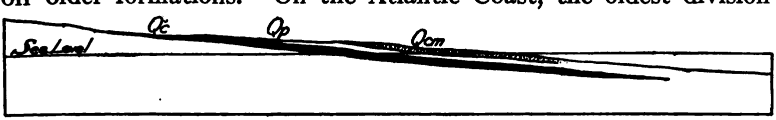



Fig. 536. Diagram showing the theoretic relations of the three principal subdivisions of the Pleistocene outside the valleys, along a line normal to the coast. The letters have the same significance as in Fig. 535.

rests now on the Lafayette formation, and now on terranes from which the Lafayette had been eroded before the deposition of the Columbia series (Fig. 537).

The Columbia series rarely contains *fossils;* but at a few points

shells of fresh-water mollusks have been found and at a few points marine shells,— all within a few feet of sea-level.

*The origin* of the Columbia formation presents much the same problems as that of the Lafayette, and is probably to be explained in much the same way. The series is looked upon as largely subaërial (pluvial and fluvial), the result of land aggradation. The

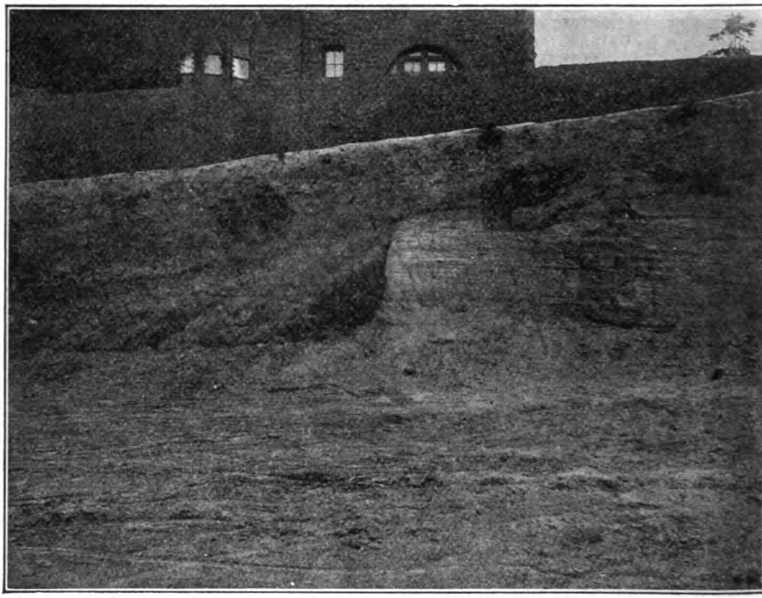


Fig. 537. Unconformable contact between the Columbia formation and the Potomac, Washington, D. C. (Darton, U. S. Geol. Surv.)

occasion for repeated intervals of deposition on the Coastal Plain, separated by epochs of erosion, probably lay partly in changes of gradient incident to surface warpings, and partly in the changes of climate of the period. (1) Slight further upward bowing of the highlands west of the coast probably stimulated the streams descending from them to increased erosion, and the deposition of a part of their loads on the plain below was a natural result. The poor assortment of the material, the common cross-bedding, the numerous trifling unconformities, and the absence of fossils, all are consistent with this interpretation. (2) The second factor contributed

to the same end. The climate of the period was changeable, and at least periodically cold, as the recurrent ice-sheets show. Under these conditons a larger proportion of the precipitation than now was doubtless in the form of snow, and this was favorable to the flooding of streams during the melting seasons. Floating ice helped to transport the bowlders of the formation, and so to give it the heterogeneity which is one of its distinctive features, especially in proximity to the glacial drift. The cold climate probably affected erosion, and therefore deposition, in another way, for the reduction of temperature probably was attended by a reduction of vegetation, and this by an increase of erosion. The reduction of vegetation presumably was greatest just where erosion was stimulated most readily, namely, in the higher altitudes.

It is conceived, therefore, that the deposition of the principal subdivisions of the Quaternary series of the Coastal Plain resulted from the combined effect of slight surface warpings and climatic changes; that epochs of notable deposition alternated with epochs when erosion was dominant in the same regions; and that the materials of each principal stage of deposition were deposited, shifted, and re-deposited repeatedly. The youngest division of the series was essentially contemporaneous with the last glacial epoch, and it seems not improbable that the earlier members were deposited during earlier glacial epochs.

In recent times, dunes have been developed at numerous points along the coast, and their development and destruction is still in progress.[1] Humus deposits also have somewhat extensive development in the tidal marshes, and to a less extent elsewhere.

**Interior.** Some of the non-glacial Pleistocene formations of the interior, notably the loess, the valley trains, etc., have been referred to. Apart from such formations, there are others which seem to be measurably or wholly independent of the ice. The widespread gravels of the western plains have been referred to (p. 599), but their deposition continued through the Pleistocene, and is indeed still in progress. There are numerous tracts and belts of dunes where conditions favor their development, as in central and western Nebraska, and Kansas. Dunes are of common occurrence locally even east of the Great Plains, as about the head of Lake Michigan and along its eastern shore. Even where dunes are wanting, wind-blown sand and dust in small quantities are widespread.

[1] See for example, the Norfolk, Va.-N. C., folio, U. S. Geol. Surv.

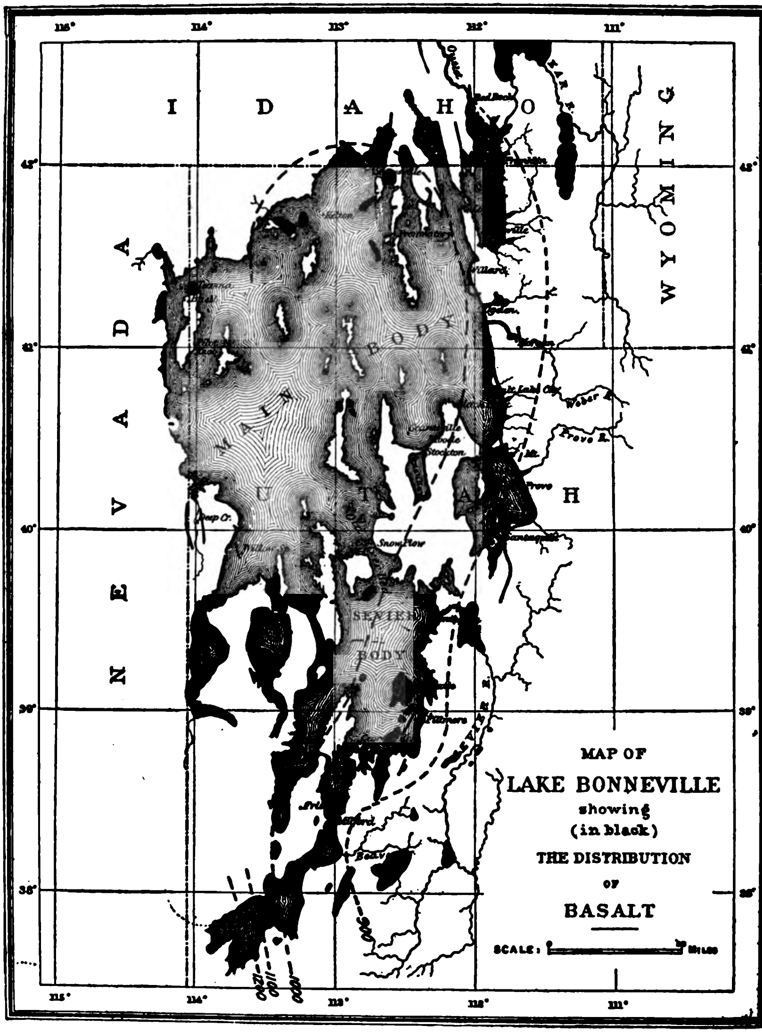



Fig. 538. Map of Lake Bonneville, showing also the areas of basalt (black areas), some of which are Quaternary, the lines of recent faulting (full black lines), and the deformation of the basin (broken lines). The numbers on the broken lines show the height of the Bonneville shore line above the level of the present Great Salt Lake, at different places. (Gilbert, U. S. Geol. Surv.)

Outside the region affected by the ice-sheets, erosion rather than deposition was the great feature of the Quaternary in the interior. In the erosion, wind, running water, and ground-water have co-operated.

**The West.** The Quaternary formations of the west belong to all the several categories mentioned on p. 652, and in addition there is much glacial drift left by mountain glaciers. Few of these various sorts of deposits have received close study over any considerable area, though something is known of all. The deposits of some of the lakes at various points west of the Rocky Mountains, especially those of the Great Basin, deserve special mention.

*Lacustrine deposits.* The most considerable of the western Pleistocene lakes was *Lake Bonneville* [1] of which Great Salt Lake is the diminutive descendant. Its basin is believed to have been due to deformation and faulting. Previous to the formation of the lake, the basin is thought to have been arid. During the period of aridity, such quantities of debris came down from the surrounding mountains as to bury their bases to depths of perhaps 2,000 feet at a maximum.

Later, climatic conditions were such as to bring a large lake into existence, but after a time it appears to have dried up, probably because of another change of climate. Still later, the lake was restored, and its water rose higher than before, and found an outlet northward. In the course of time, evaporation from the lake again became greater than precipitation and inflow, and the lake gradually shrank until it became Great Salt Lake. At its maximum, Lake Bonneville was more than 1,000 feet deep, and had an area of more than 19,000 square miles; the maximum depth of Great Salt Lake is less than 50 feet (average less than 20), and its area but about one-tenth that of its ancestor.

Terraces, deltas, and embankments of other sorts were developed about the shores of Lake Bonneville wherever the appropriate conditions existed (Figs. 202 and 539), and because of the aridity of the climate since the lake sank below them, they have been modified but little by erosion. As the lake dried up, deposits of salts were made, among which sodium chloride and sodium sulphate are most abundant. Great Salt Lake is estimated to contain 400,000,000 tons of common salt, and 30,000,000 tons of sodium sulphate.

Igneous eruptions (Fig. 538) have taken place in the basin at

[1] Gilbert, Mono. I, U. S. Geol. Surv.

various stages of the lake's history, and even since Lake Bonneville disappeared. Since this time, too, there has been faulting in the basin, with displacements of as much as 40 feet (Figs. 538 and 541). Furthermore, the shore lines of the former lake have been warped so that some parts are more than 300 feet higher than others (Fig. 538).

Farther west, but still in the area of the Great Basin, were other lakes, probably contemporaneous with Bonneville. Among them

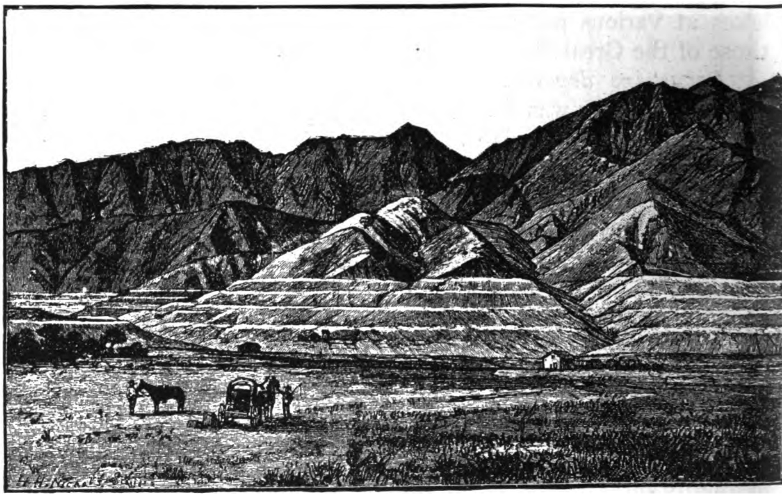


Fig. 539. Shore of former Lake Bonneville, Wellsville, Utah. (U. S. Geol. Surv.)

Lake Lahontan [1] was of importance. Its history and that of a lake which occupied a part of Mono Valley, California, were similar to that of Lake Bonneville.

*Glacial effects.* The extent of glaciation in the western mountains was outlined in the early part of this chapter. The erosive work of the mountain glaciers was considerable, as shown both by the extensive deposits of glacial drift, and by the forms of the valleys which the glaciers occupied. The most massive accumulations of drift are in the form of lateral moraines, which in some cases are nearly or quite 1,000 feet high. Under the conditions of active drainage which existed in the mountains, much of the glacial

[1] Russell, Mono. XI, U. S. Geol. Surv.

debris was carried beyond the ice by the water flowing from it, and deposited in the valleys and "parks," or on the plains below. Glacial cirques, the result of a peculiar phase of glacier erosion, are

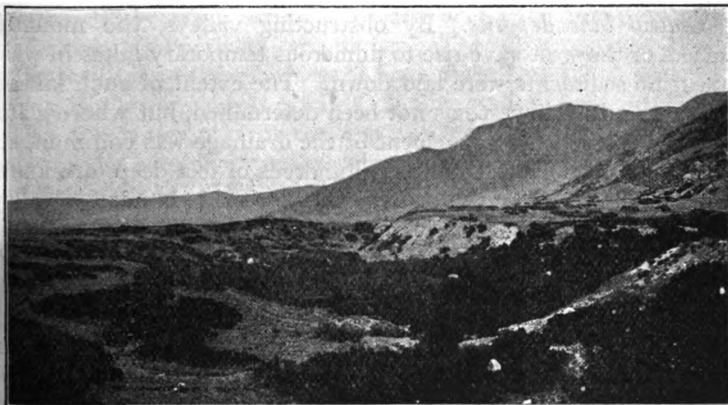


Fig. 540. Faulting on the shore of Lake Bonneville. (Church.)

well developed in many of the glaciated valleys as, for example, in the Uinta Mountains.

The characteristics of mountain valleys which were occupied by considerable glaciers are essentially constant. They include (1) well developed cirques at the heads (Pl. XIII); (2) the upper parts of the valleys were so thoroughly cleaned out by the ice that little loose debris, except that due to post-glacial weathering, remains; (3) numerous tributary valleys are hanging (Fig. 151), and their waters form cataracts; (4) at and near the limits of the ice,

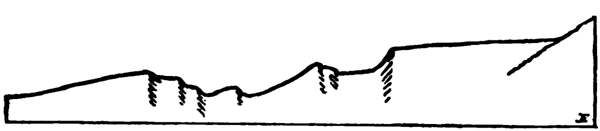


Fig. 541. Fault scarps in the moraine at the mouth of the Little Cottonwood Canyon, Wasatch Mountains. (Gilbert, U. S. Geol. Surv.)

at stages when its end or edges remained for a time nearly constant in position, there are heavy accumulations of drift, lateral moraines being as a rule more conspicuous than terminal; (5) the valleys

contain lakes (Pl. XIII), some of which occupy rock basins, and some basins produced by drift dams; and (6) valley trains or outwash plains below the moraines. The partial removal of these deposits has developed terraces (Fig. 124).

*Glacial lake deposits.* By obstructing valleys, the mountain glaciers of the west gave rise to numerous temporary lakes in which lacustrine sediments were laid down. The extent of such lakes in the west and northwest has not been determined, but where glaciation was extensive, derangement of the drainage was common, and deposits of glacio-lacustrine clay, hundreds of feet deep, are known at some points. Where such deposits were made in narrow valleys now drained, they have been removed in part, and their remnants constitute terraces.

*Alluvial and talus deposits.* In the basin region of Utah and Nevada there are exceptional deposits of detritus, the accumulation of which was favored by topography and climate. The mountain ranges of the basin region are separated by broad depressions. From the steep slopes, detritus is carried down both by descending torrents and by gravity, and while it is largely deposited at and against the bases of the mountains, some of it is spread widely over the surrounding plains. This debris is mainly unstratified, or poorly stratified, and some of it is very coarse. It appears in greatest quantity where canyons issue from the mountains, and in such situations there are huge fans of bowlders, some of them 1,000 feet in height. The torrents were able to carry this coarse material so long as they were confined within the canyons, but with the change of gradient below, the water gave up its load. As the glacial deposits increase in importance to the north, talus and other subaërial accumulations become less conspicuous, and are much less considerable in Montana, Idaho, and Washington than in the more arid and unglaciated regions farther south.

*Eolian deposits.* The wind is an important agent of erosion and deposition in the west. Its erosive work is shown in the peculiar carving which affects the cliffs and projections of rock at many points (Fig. 14), and its depositional work by the dunes, which are not rare. The erosive work of the wind here is far greater than is commonly appreciated by those unfamiliar with arid regions.

*Deposition from solution.* About many springs, as in the Yellowstone Park, deposits of siliceous sinter and calcareous tufa are now making (Fig. 31). Considerable deposits of a similar nature

antedate the present by a notable interval of time, but probably fall within the limits of the Quaternary period.

*Marine deposits.* At some points along the western coast of the United States marine deposits extend inland some distance from the sea. They reach altitudes of 200 or 300 feet in California[1] and Oregon, and perhaps even higher. The submergence indicated by the position of these beds must have given origin to considerable bays in the lower courses of the Columbia and Willamette valleys. By far the larger part of the marine Quaternary deposits of the coasts of the continent are still beneath the sea.

*Igneous rocks.* The Quaternary eruptions of North America have not been separated clearly from those of the late Tertiary, but there are some igneous rocks which are Quaternary, some of them even late Quaternary. Mount Shasta shows several post-glacial lava-flows, and there are small cinder cones on alluvial cones at the east base of the Sierras in southeastern California. In southern California (Mohave Desert) and northern Arizona (vicinity of Flagstaff) there are cinder cones and lava-flows of limited extent which are so slightly touched by erosion that there can be little doubt that they date from a time long subsequent to the beginning of the Quaternary period. Judged by the same criteria, there are lava-flows and cinder cones of Quaternary age in New Mexico, Colorado, Utah, Nevada, Oregon (p. 230), Idaho, Washington, and at various points in the Sierras.[2] On many of them vegetation has hardly begun to gain a foothold. Gilbert estimates that of 250 lava-fields observed in these states, 15% are of Pleistocene age, and of 350 volcanic cones in the same states, 60% are considered to be Pleistocene.[3] Volcanic ash is interbedded with loess at various points in eastern Washington and Oregon,[4] and overlies glacial moraines in some parts of Alaska.

## CHANGES OF LEVEL DURING THE PLEISTOCENE

The very considerable changes of level which marked the closing stages of the Pliocene have been mentioned, and many of them doubtless continued into the Pleistocene. Minor movements of later date, such as those which affected the basins of Lakes Bonneville and Lahontan during the Pleistocene also have been noted.

[1] Ashley, Jour. Geol., Vol. III, pp. 446–450.

[2] See published folios of Washington, Oregon, California, and Idaho.

[3] Mono. I, U. S. Geol. Surv., pp. 323–337.

[4] Jour. Geol., Vol. IX, p. 730.

Such changes are probably but a meager index of the crustal warpings of the period. Specific data on this point are less abundant than could be desired, for the phenomena of erosion and deposition which followed the elevation at the close of the Tertiary are not readily differentiated from similar phenomena resulting from later elevations. Nevertheless, evidence of Pleistocene changes of level, as distinct from late Pliocene, are not wanting, especially near the coasts and about the shores of the Great Lakes.

From the evidence at hand, it appears that deformative movements were widespread both in the western mountains and in the area covered by the great ice-sheets. In general, the areas covered by the ice-sheets have risen since the ice melted. It is a tenable hypothesis that the rise, or some part of it, resulted from the melting of the ice, and that it followed a depression caused by the weight of the ice. The rise of the land has been greatest, on the average, where the ice was thickest. This rise of the glacial centers is shown in various ways, but especially by the raised beaches along the coasts, and by the deformed shore lines of the interior lakes. Thus the shore lines of Lake Agassiz are considerably higher at the north than at the south, their inclination being as much as a foot to the mile in the northern part of the basin. The shore lines of Lake Iroquois (p. 639) decline from the northeast to the southwest at the average rate of three and a half feet per mile. The beaches of Lake Algonquin (Fig. 530) are 25 feet above the present lake at Port Huron, and 635 feet above the lake at North Bay, Ontario. The shore lines of the other lakes show comparable warping.

There have been changes of level, though less extensive in most places, in regions which were not glaciated. Thus along the Atlantic coast south of the drift there have perhaps been complex movements, but of no great range, in the course of the period. On the whole, elevation (relative) appears to have exceeded depression, but the latest movement (present) appears to have been one of sinking, as the drowned ends of the valleys show.

It is not improbable that movements of equal magnitude have affected the interior regions of the continent, but, except about the lakes, there is no datum plane like the sea-level to which these changes may be readily referred. In a few places, local deformation is notable. In New York and Ohio, the solution of underlying gypsum and salt is suspected of being the occasion of some of the slight deformations observed.

Some of the islands of Southern California seem to have risen, relatively, some 1,500 feet since the Pliocene. Other parts of the California coast, and some of the adjacent islands, have been sinking during the same period.[1] Near San Francisco, the surface is thought to have ranged from 1,800 feet below its present level to 400 feet above. Along the northwestern coast of Oregon, a rise of at least 200 feet during the Pleistocene[2] has been estimated.

### *Foreign*

The salient points in the glacial history of Europe have been sketched, and some indication has been given of the extent of the deployment of ice in other continents. It need only be added here that outside the areas affected by the ice, there are, in all continents, accumulations of sediment of the sorts just enumerated. In Europe there are cave deposits of Quaternary, perhaps of glacial, age, which are of interest because they contain human relics, probably the oldest known. The relics consist of rude stone implements, bones of mammals with human markings on them, and bones of human beings.

## LIFE

**Destructive effects of glaciation.** We must believe that the successive ice-sheets, several million square miles in extent, destroyed much life, and caused great changes in that which survived; yet, so far as the record shows, the difference between preglacial life and post-glacial life is less than might have been expected. More than half the known species of marine Pliocene invertebrates are still living, though in the transition between several of the more ancient periods, nearly all species disappeared. Of Pliocene plant species, too, many are still living; but the land vertebrates of that period were very generally replaced by new species, and the same appears to be true of the insects.

When the ice was most extensive, the sum total of life on the earth must have been reduced greatly. Even the life of to-day is probably less in amount than that of the middle Tertiary. Not only this, but existing life is probably but poorly adjusted to its surroundings, for it is improbable that, in the millions of square miles where life was destroyed by the ice, there has yet been worked out the

[1] Lawson, Bull. Dept. Geol., Univ. of Calif., Vol. I. Reviewed in Jour. Geol., Vol. II, p. 235.

[2] Diller, 17th Ann. Rept., U. S. Geol. Surv., Pt. I.

best balance (1) between the vegetation and the soils and climate on which it depends, (2) between plants and herbivorous animals, and (3) between the carnivorous animals and the herbivores on which they prey.

**To-and-fro migration.** An important biological effect of the ice-sheets on life, was forced migration. With every advance of the ice, the whole fauna and flora of the region affected had to move on in front of it, or die. The arctic species along the ice border crowded upon the sub-arctic forms just south of them, these in turn crowded upon the cold-temperate species beyond, and so on. It is not unlikely that even the tropical zones were somewhat narrowed. During the interglacial epochs, migrations were reversed. As the advances and retreats of the ice caused migrations back and forth, every organism was obliged to adapt itself to a new zone, to migrate, or to die. There appear to have been four or five such to-and-fro migrations in America and Europe, and the extent of the migrations was several hundred miles, and in some cases perhaps one to two thousand miles. During some of the interglacial epochs, the life of middle latitudes indicates a climate milder than the present, and this implies that the ice-sheets were reduced at least as much as now. During some of the interglacial epochs, northern lands seem to have supported as many plants and animals as now. Geological evidence warrants the belief that at least some of the interglacial intervals were long enough, and their climates warm enough, to permit a complete northward return of the life which was forced south during glacial epochs.

**Relics of glacial migrations.** Significant evidence of the to-and-fro migrations of the period is found in the life of the higher mountains within or near the borders of the once glaciated areas. When the ice was near these mountains, arctic life only could have existed there. As the ice retired to the north, the arctic life of the surrounding lowlands moved northward also, and life from the temperate zone came on to take its place; but in the mountains the arctic life still found congenial conditions by moving up to higher and higher levels as the climate became warmer. In this way arctic life became isolated in the high mountains. Plants, insects, and small mammals whose kin now live in the arctic zone, remain to this day in some of the higher parts of the northern Appalachians, and the same point is still more strikingly illustrated in the Alps.

**Life of interglacial epochs.** By far the larger part of the fossils

whose exact relations to the ice invasions can be fixed are found in the interglacial beds. Of these, the most instructive which have been studied carefully in America are those on the Don River and in the Scarboro cliffs, near Toronto.[1] The fossil-bearing beds are underlain by a sheet of bowlder clay older than the late Wisconsin sheet of drift. The upper surface of this underlying till was eroded before the overlying fossiliferous interglacial beds of stratified sand and clay were deposited upon it. After the erosion of the latter, a thick body of drift of Late Wisconsin age was deposited upon it.

The lower part of these interglacial beds contains fossils of a warm-temperate fauna and flora, while the upper contains the relics of a cold-temperate fauna and flora. Up to 1900, the lower beds had yielded 38 species of plants, many of which indicate a climate appreciably warmer (3° to 5°) than that of the same region now. Among these are the pawpaw and the osage orange, which now flourish farther south. The fauna includes about 40 species of mollusks, some of which are now living in Lake Ontario, some in Lake Erie, while some are not known in the waters of the St. Lawrence system. The fossils of the upper beds include 14 species of plants, and 78 species of animals, mostly beetles. This assemblage implies a climate of about the type which now prevails in southern Labrador. The arctic fauna and flora which should have followed this cold-temperate one, marking the approach of the next ice-sheet, are undiscovered.

In other interglacial formations there is evidence at many points of an ample growth of vegetation, recorded in peat and muck beds, in humus-bearing soils, and in twigs, limbs, trunks, etc., of trees, but from them few species have been identified. Recently, bones of horses (more than one species) have been found in the Aftonian interglacial beds in Iowa,[2] along with bones of elephants and mastodons.

### *Marine Life*

**On northerly coasts.** During that stage of the Wisconsin glaciation when the eskers of Maine were being formed, and the sea-level stood higher than now relative to the land along that part of

[1] Coleman, Interglacial Fossils from the Don Valley, Toronto, Am. Geol., Vol. XII, 1894, pp. 86–95, with references to earlier literature; also Glacial and Interglacial Beds near Toronto, Jour. Geol., Vol. IX, 1901, pp. 285–310. Professor Coleman thinks (1913) that the Don beds are of Aftonian age.

[2] Calvin, G. S. A., Vol. XX.

the coast, arctic mollusks lived along the shore and were buried in marine clays deposited while the eskers were being made.[1] The same species live now in waters that are near the freezing point most of the year. Remains of walruses, seals, and whales also have been found. When an arm of the sea occupied the lower St. Lawrence and Champlain valleys (p. 640), it was peopled by a marine fauna similar to that which now lives about the mouth of the St. Lawrence and on the coast of Labrador.

**On southerly coasts.** Away from the immediate influences of the ice-sheets, the record of marine life does not indicate any profound departure from the progressive modernization that had been in progress through the Tertiary period. It has been stated by Dall that the Pleistocene fauna of the Atlantic coast does not imply as cold waters as the Oligocene fauna does, and by Arnold that the Pleistocene fauna of the California coast does not indicate a climate as cool as that of the Pliocene. It is to be noted, however, that the known marine record may not cover more than a small part of the Pleistocene period, and it is not certain — perhaps not probable — that the portion represented corresponds to any one of the glacial epochs. When the ice was pushing into the ocean on the coast of Maine, as in the late Wisconsin epoch, and an arctic fauna occupied that coast, it is scarcely probable that a warm-temperate fauna lived on the southern coast; nor is it probable that, when icebergs were being discharged into Puget Sound, and along all the coast farther north, a warm-temperate fauna lived on the California coast; but warm-temperate faunas on those coasts during interglacial epochs are entirely consistent with a climate such as that suggested by the Don River beds.

### *Terrestrial Life of Non-glaciated Regions*

The life of the lands far from the glaciated areas cannot now be correlated closely with the glacial and interglacial stages. In North America, northerly types such as the mammoth and mastodon, the bear, bison, reindeer, and musk-ox, apparently driven south by the advancing ice, were characteristic of these faunas. In the mid-latitudes of North America there were several types on the verge of extinction, such as the horse, tapir, llama, and saber-tooth cat. It is not improbable that there was intermigration with Eurasia by

[1] Stone, Mon., U. S. Geol. Surv., XXXIV, 1899, pp. 53–54, and Bastin, Rockland, Me., folio, U. S. Geol. Surv.

the northeastern (Greenland-Iceland) or northwestern (Behring Strait) routes during the interglacial epochs. Another prominent feature of the land faunas far from the ice was a group of southern forms consisting of gigantic sloths, armadillos, and water-hogs, whose forebears had come from South America a little earlier, by way of the Isthmus of Panama.

**The boreal group.** As in the Pliocene, proboscidians dominated the fields and forests of middle latitudes. The mammoth ranged

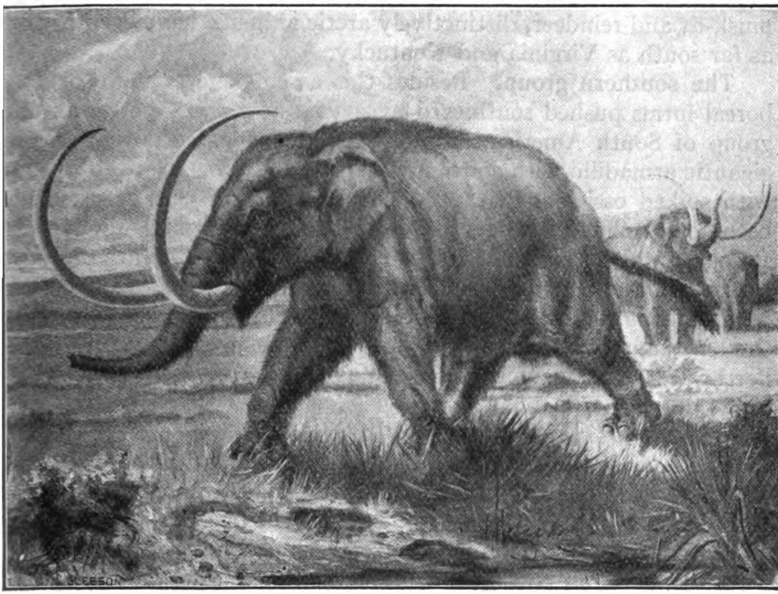


Fig. 542. An interpretation of *Mastodon americanus* by G. M. Gleeson. (From painting in National Museum, Washington.)

from Mexico northward, reaching Canada and Alaska during interglacial epochs. In Siberia, the mammoth was covered with wool and hair, and was obviously adapted to a cold climate. The mammoth survived the glacial period in America, and its tusks and skeletons are found in beds of peat and muck which have accumulated since, in northern United States and Canada. The mastodon also ranged northward into Canada, but since it emigrated to South America and crossed the tropics, it must have been adapted to a

warm climate also. It likewise outlived the glacial period. Williston suggests that while mammoths were abundant on treeless plains, mastodons were confined mostly to valleys and forests, notably those of the eastern states, the eastern part of the Mississippi basin, and the Pacific coast.

Several species of horses have been found in western beds referred to the Pleistocene period. A gigantic elk ranged from Mississippi to New York. Two or three species of buffaloes roamed over the Ohio valley and southward to the Gulf, and remains of the musk-ox and reindeer, distinctively arctic animals, have been found as far south as Virginia and Kentucky.

**The southern group.** Besides this assemblage of more or less boreal forms pushed southward by glacial advances, there was the group of South American immigrants, the monster sloths, and a gigantic armadillo with a strong carapace and a massive tail plated with spiked ossicles (Fig. 543). The remains of this group have been found chiefly in caverns, in the muck and mire about salt springs, and in fluvial deposits, the precise ages of which are difficult to fix. In the climate of such an interglacial stage as that which permitted pawpaws and osage oranges to flourish about Toronto, there was apparently nothing to prevent these animals from ranging northward to Pennsylvania and Oregon.

### *Life in Eurasia*

The faunas of Europe underwent changes similar to those already sketched for America. During the first glacial epoch, an arctic fauna lived in the North Sea, while during the first recognized interglacial epoch, the arctic fauna retreated northward. At this time a flora comparable to that now living in England was found in the British Isles, while the hippopotamus, elephant, deer, and other mammals invaded Britain by way of the land bridge which then connected it with the continent. A similar flora and fauna advanced to corresponding latitudes on the mainland. A luxurious deciduous flora lived in the valleys of the Alps, and up to heights which it no longer attains. Toward the close of this interglacial epoch the temperate flora gave place to an arctic flora.

During the second glacial epoch, according to Geikie,[1] the ice reached its maximum extent in Europe, and arctic-alpine plants occupied the low grounds of central Europe, while northern mam-

[1] The Great Ice Age, Third Edition, pp. 607–615.

mals, including the reindeer, the arctic fox, etc., reached the mountains of southern Europe, and even the shores of the Mediterranean. During the second interglacial epoch, a temperate flora and fauna succeeded the arctic ones which had just preceded. The plants which then occupied northern Germany and central Russia imply a climate milder than the present, and the mammalian fauna, which included the hippopotamus and elephant (*Elephas antiquus*), was in keeping with the flora. Toward the close of this interglacial epoch, northerly forms began to appear, and as the third glacial

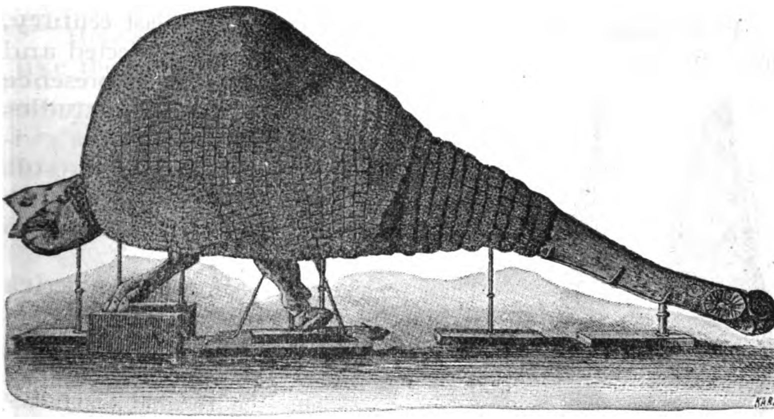


Fig. 543. A club-tailed glyptodon, *Dædicurus clavicaudatus*, from South America. (Lydekker.)

epoch came on, northern types advanced well to the south. In the third interglacial epoch the climate seems to have been congenial to a cool-temperate fauna.

During the remaining epochs the oscillations of the ice apparently were less. Corresponding to these diminishing oscillations the to-and-fro migrations of life appear to have become less extensive.

**Pleistocene life of other continents.** While the Pleistocene life of North America was similar to that of Europe, that of *South America* had a character quite its own. Its most distinctive features were (1) gigantic sloths and armadillos, indigenous to South America and very numerous, and (2) descendants of the Pliocene mammals which had migrated from North America. Among the northern immigrants were horses, mastodons, llamas, tapirs, wolves, and a variety of rodents.

Owing to the isolation of *Australia*, its life was peculiar to itself. The vertebrate fauna consisted of marsupials and monotremes exclusively. In general, they differed specifically from those now living, and were, on the whole, larger. Although glaciers had but slight development in Australia, the effects of the widespread refrigeration of the higher latitudes was doubtless felt. Comparatively little is known of the Pleistocene life of *Africa*, but a moderate climate in the northern portion seems to be indicated.

### *Man in the Glacial Period*[1]

**In America.** Previous to the last decade of the last century, much prehistoric material of human origin had been collected and widely accepted as proof of man's presence in America in glacial times; but later studies have disclosed weaknesses both in the evidence and in its interpretation. The result is that man's antiquity in America is a more open question to-day than it was thought to be twenty years ago.

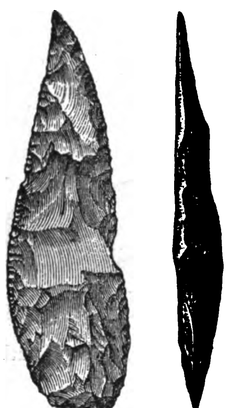


Fig. 544. A typical paleolith from Kent's Cavern, Torquay, England, seen on the face and edge. (Evans.)

These prehistoric human relics in America range from the rudest stone chips and flakes to skillfully fashioned and polished handiwork in stone, metal, and bone. Following European precedent, the rougher artefacs[2] were classed as *paleolithic*, and interpreted as indicating the presence of Paleolithic man (and of the Paleolithic or Old Stone age) in America. The more perfectly fashioned artefacs were classed as *neolithic*, with corresponding reference to the Neolithic (New Stone) age. Some students properly regard "paleolithic" and "neolithic" as *stages of early art*, not as chronological "ages," or geologic divisions, though the terms have been much used in the latter sense.

The relics interpreted as paleoliths consist chiefly of rudely chipped pieces of flint, quartz, argillite, etc. (Fig. 544). The neoliths

[1] See references, p. 676.

[2] The term "artefac" designates any object fashioned by man, in any way or for any purpose, or, incidentally, without purpose. It includes stone chips, broken and rejected material, and various forms of by-products, as well as implements, weapons, ornaments, etc.

include a wider range of stone artefacs, typified by well-chipped arrow-points, spear-heads, knives, and scrapers of flint or quartz, and by the ground and polished axes, chisels, pestles, mortars, and other implements of greenstone and similar tough or workable rock. The paleoliths, as defined above, were interpreted as the work of an earlier and less cultured people, while the neoliths were known to have been the implements and weapons of the natives of the continent when first invaded by Europeans. It is to be noted that the phase of the stone art designated "neolithic" was dominant on the continent until recent times, and is scarcely yet extinct.

Holmes [1] has shown that the early inhabitants of the country, like the later Indians, went habitually to gravel-beds and to out-

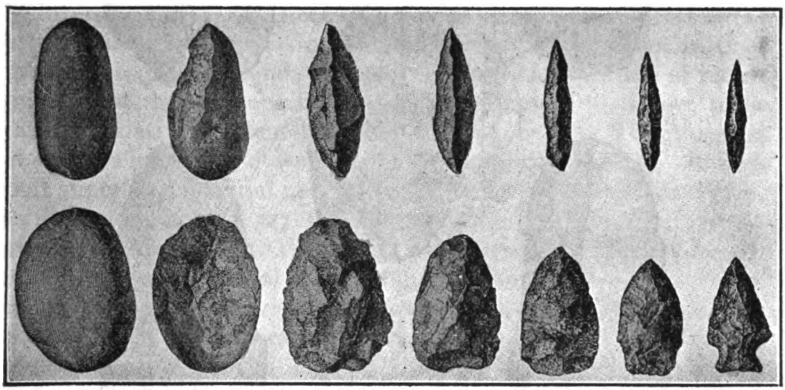


Fig. 545. A series of forms illustrating progressive steps in the manufacture of arrow-points from quartz pebbles obtained mainly from shops and village-sites, near Anacostia, D. C. (Holmes.)

crops of appropriate rock to procure the raw material for their stone artefacs, and that it was their custom to test and to rough-out the material on the ground, leaving the chips and rejected material scattered about when the rough work was done. The more delicate work of shaping the rough material into implements was apparently done as need required, at their villages or at other convenient places

[1] Holmes, W. H., A Stone Implement Workshop, Am. Anthropologist, Vol. III, 1890, pp. 1–26; Review of the Evidence Relative to Auriferous Gravel Man in California, Smith. Rept. 1900, pp. 417–472; Stone Implements of the Potomac-Chesapeake Tidewater, Ann. Rept. Bureau of Eth., 1893–94, pp. 1–152, and Jour. Geol., Vol. I.

to which stone from the quarries was carried. The stages of manufacture, as thus interpreted, are shown in Fig. 545.

Because of this separation of the process of manufacture into

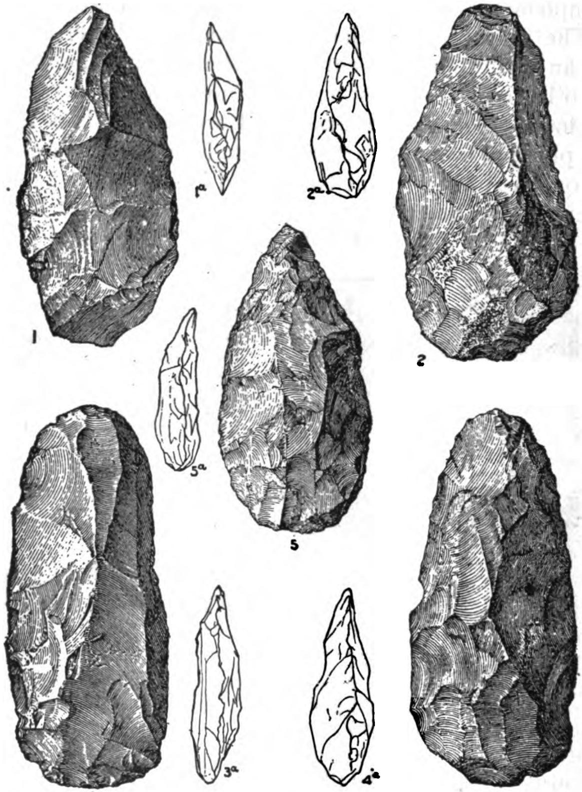



Fig. 546. A group of figures of chipped-stone artefacs, one of which has been regarded as a typical paleolithic implement, front and side view. The rest were obtained, in three cases, from modern flint-shops of the region in which the supposed paleolith was found, while the fourth was traceable directly to the same shops. The discrimination between the paleolith and the rejects is left to the reader. (Holmes.)

two parts, (1) roughing out at the quarries, gravel-beds, etc., and (2) shaping tools at dwelling sites or elsewhere, there arose a geographic separation of the products. The rude failures and rejects, together with the extemporized hammer-stones, cores, flakings, and

chips, were scattered about the sites of the raw material, while the completed implements are liable to be found only about the dwelling sites, or where, in their use, they were lost or thrown aside. In the light of this definite separation, it is not difficult to see how the idea of two stages of art arose, and how easily the finds might be misinterpreted.

The most available sites for finding suitable raw material in a convenient form were river gravels and terrace formations. This was especially true in and about the glaciated regions where glacial gravels abounded. In them, quartz, flint, chert, etc., were usually abundant, in the convenient form of pebbles and cobbles.

Many of the rude artefacs in question ("paleoliths") have been found chiefly in such gravels, and it was this which cuased them to be interpreted as proving the existence of glacial man. Most of the artefacs in valley gravels are in their superficial portions, in their talus slopes, or in secondary deposits, many of which are of recent origin. Of the less superficial finds, many have been shown to be cases of relatively recent burial by natural means. The processes of streams in cutting down their channels in valley gravels are such that superficial material may be buried to very considerable depths, as illustrated in Figs. 547–549. The material which was in the top originally, may get into the base of the talus, and be buried deeply. Similar secondary burial takes place in all sorts of loose material of eolian, pluvial, and fluvial origin; and it is to be noted that this is a normal process, not an exceptional one. There are other ways, too, notably scour and fill (p. 112), in which human relics may be buried in river gravels.

Without further details, it may be said that human relics have not been found, in America, in gravels known to have been deposited in the glacial period, or before. All that have been reported from glacial gravels have been found either in such positions as to show that they were buried in post-glacial time, or in such positions as to make this inference probable. The existence of man in America in the glacial period or before is therefore not demonstrated.

**In Europe.** The European data indicating great antiquity of man are better than the American. In Europe there are numerous caves in which the relics of man, mingled with those of extinct animals, have been securely protected by layers of stalagmite. While the ages of the stalagmite layers have rarely been fixed with certainty, or well correlated with the glacial stages, they bear

inherent evidence of considerable antiquity. The European cave evidence seems to have no strict counterpart in America.

The association of man with extinct animals is a phenomenon that may mean the extension of man's presence backward, or the extension of the animals' presence forward; and to this double-faced problem research has not yet furnished a final key. Obviously,

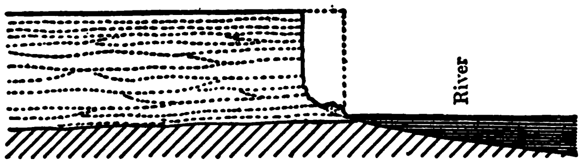



Fig. 547. A gravel bluff formed by the undercutting of the adjacent river. (After Holmes.)

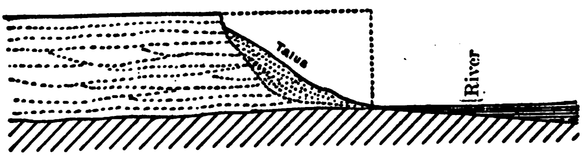



Fig. 548. The same at an early stage of talus formation.

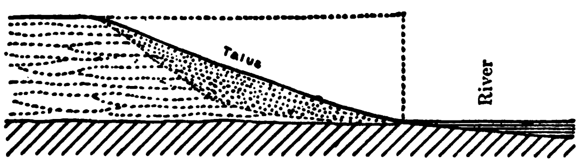



Fig. 549. The same at a late stage, when the slope has become nearly stable.

however, the larger the number of animal types not known to have lived this side the last glacial stage whose remains are commingled with human relics, the stronger the presumption of man's presence before the close of the glacial period. From this point of view, the European case seems to be strong.

There is one further feature in the European case that is, at least, suggestive. Two climatic groups of animals are associated

with the human relics—a subarctic and a subtropical. In the subarctic group there were reindeer, mammoths, woolly rhinoceroses, musk-oxen, and other boreal forms; in the subtropical group, lions, leopards, hippopotamuses, hyenas, southern rhinoceroses, and other African types. These contrasted groups, as interpreted by James Geikie and others, imply migrations of the kind already sketched as characteristic of the glacial period. These seem to indicate, therefore, that man lived in Europe before the close of the glacial period.

The relics thus associated with extinct animals have been assigned to paleolithic man, and to a primitive stage of culture. This interpretation is based on the crudeness of the stone artefacs,

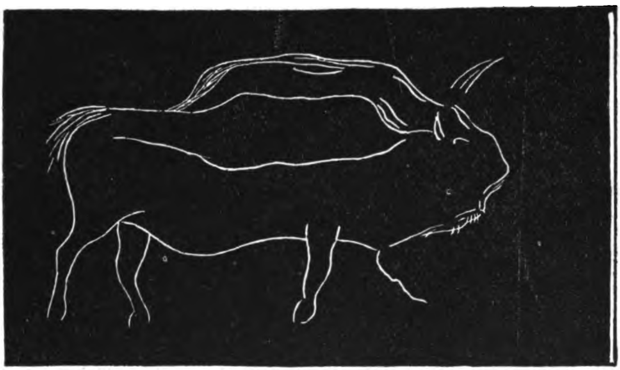


Fig. 550. Etching of an aurochs on a slab of slate, from the bone cave of Les Eyzies, Dordogne, France (½ size). This sketch may be instructively compared with the similar work of the ancient Assyrians and Egyptians. (Prestwick.)

rather than upon the evidence of a higher order of art which the record presents. If, however, the rude stone artefacs can be interpreted as the waste incidental to the making of good stone implements, a more favorable judgment of the art of these ancient peoples would be reached. Associated with the ruder artefacs (or paleoliths) there are implements of bone, such as needles, awls, harpoons or spears with barbs, etc., implying some advance in art; there are carvings that show not a little skill, and drawings in which the elements of perspective and shading, as well as skill in delineation, are indicated (Fig. 550). These seem to imply a higher stage of art development than is consistent with the exclusive use of paleolithic

stone implements. On the whole, present evidence seems to justify the conclusion of most European archæological geologists that man was present in southern and central Europe during the later part of the glacial period, and perhaps even early in the period. A recent discovery in Switzerland would seem to place the beginning as far back as the interglacial[1] epoch which may correspond with the North American Yarmouth (p. 634).

*A few references relative to the antiquity of man:* Chamberlin, T. C., Jour. Geol., Vol. X; Geikie, James, The Great Ice Age, pp. 616–690; and Prehistoric Europe, pp. 568 et seq.; Gilbert, G. K., Sci. Am. Supp., Vol. XXIII, 1887; Lyell, Sir Charles, Antiquity of Man; McGee, W. J., Am. Geol., Vol. XXII, pp. 96–126; Sci., new ser., Vol. IX, pp. 104–105; Upham, Warren, Science, Vol. XVI, pp. 355–6; Am. Geol., Vols. XXX and XXXI; Whitney, J. D., Am. Jour. Sci., 2d ser., Vol. 43, pp. 265–267, 1867; The Auriferous Gravels of the Sierra Nevada of California, Cambridge, 1879.

[1] Science, Vol. XXIX, 1909, p. 359.

# CHAPTER XXX

## THE HUMAN OR PRESENT PERIOD

**The end of the glacial period.** The close of the glacial period is usually placed at the time when the ice-sheets disappeared from the lowlands in the middle latitudes of Europe and North America. Notwithstanding this usage, the ice-sheets had not then disappeared completely, and have not even now, for about 10% of the recently glaciated area of North America (chiefly in Greenland) is still buried in ice. These relics of the last glacial epoch show that the continent has not yet emerged completely from the glacial period. Indeed it is not absolutely clear that there may not be another increase of ice before the long series of glacial epochs closes, but the probabilities seem to be against it.

It is not wholly clear that the deformative period which began in the late Tertiary, and extended through the Pleistocene, is yet completed. We are accustomed to regard it so, and perhaps this position is justified; but the movements of post-glacial times are not to be ignored (p. 661). A recent movement in the region of the Great Plains seems to be suggested by certain physiographic features. Many phenomena suggest that the western side of the Great Plains was lower than now, relatively, until about the close of the glacial period. On the western side of the continent there is much evidence of recent movement, some of which appears to have taken place since the close of the glacial period, as usually defined. Similar phenomena are found in other continents. It is not wholly clear, therefore, whether the present is to be regarded as a part of that period of deformation which had its climax in the Pliocene, or whether it is rather the initial stage of a period of quiescence now being entered upon.

### FORMATIONS

The formations which have been making since the end of the glacial period are similar to those of that period, except that glacial drift is now being made in limited areas only. Most marine

post-glacial formations remain beneath the sea, and are not available for study. The general character of the formations being made will be readily inferred from what has been said in earlier chapters.

## LIFE

In the seas, and on the land in the tropics, the life of the Pleistocene period appears to have passed by imperceptible gradations into that of the present. In the higher latitudes the transition was marked by two exceptional features, the re-peopling of the lands depopulated by the ice, and the invasion of the human race.

**Re-peopling the glaciated areas.** The re-peopling of the northwestern half of North America by plants and animals after the retreat of the last ice-sheet was a great event of its kind. Certain plants that abounded in Europe before the glacial period were forced across the Mediterranean, or southeastward into Asia, and did not recross the barriers of water and desert when the climate of Europe became mild again. No such barrier intervened in North America. There was, however, an ill-defined climatic barrier between the arid plain region of the southwest and the humid forest region of the southeast. There is abundant evidence that open plains and arid climates had developed in the middle latitudes of the west by the later part of the Tertiary, and that these have persisted, perhaps with brief interruptions, till now. The preglacial arid tracts of the west seem to have been distributed much as now, while the eastern half of the continent was more moist, and covered with forests.

As the floras and faunas of the western mountain region were driven south by the ice, they were hemmed in by mountain barriers at the sides, and resisted by arid lands in front. As the trend of the mountains was mainly north and south, they defined a series of meridional tracts which directed the life migrations.

In the eastern half of the continent, forests and forest-life were driven southward in a more unrestrained way, but for the most part they kept within the eastern humid tract.

Following the last ice-retreat, the life of each of these sections moved northward, expanding as it went. The arctic or tundra flora and fauna that had probably been crowded into a narrow zone fringing the ice-sheet, moved northward through about 20°, and expanded to a breadth of 600 or 700 miles in the northern part of the continent, and occupied the arctic islands not covered by

perennial ice and snow. The zone of this arctic flora and fauna now lies mostly north of 60°. The subarctic zone of stunted conifers moved northward about 12°, and expanded to a width of 400 to 600 miles. The cold-temperate belt of deciduous and evergreen trees moved a less distance, but expanded almost equally, while the warm-temperate flora spread over the territory abandoned by the last.

With each of these vegetal zones went the appropriate fauna. The musk-ox, whose remains have been found skirting the glaciated area in Pennsylvania, West Virginia, Ohio, Kentucky, Oklahoma, Missouri, and Iowa,[1] has since retired to the extreme arctic regions. The reindeer, which had a similar distribution about the edge of the ice, occupies the barrens of the northern border of the continent, while fur-bearing animals distributed themselves through the three northerly zones.

At the south the floras and faunas of the southeast spread westward but little, but the arid and prairie floras and faunas of the southwest spread eastward at the expense of the southeastern group. This does not seem to be equally true in the higher latitudes, where the trees of the eastern group are distributed far to the northwest.

The arid and semi-arid floras and faunas of the southwest seem to have pushed the more boreal and arboreous forms to the northward, or forced them to ascend the mountains; but the movement was less sweeping and more complicated than that of the east, because of topographic interference and the effect of the lingering mountain glaciation.

## *The Dynasty of Man*

**Human dispersal.** As yet there is little geologic evidence relative to the place of man's origin, or to the earliest stages of his development. Various considerations connected with his physical nature and his distribution seem to point to the warm zone of the eastern hemisphere, perhaps southern Asia or northern Africa, as the place of his appearance. There are some grounds for the inference that the earliest developments of those qualities that gave him dominance were associated with the open tracts of the subtropical zone, rather than with the forests of the equatorial belt. Subsequent history, as well as the nature of the case, teaches us that

[1] Hay's Catalogue of Fossil Vertebrates in North America, Bull. 179, U. S. Geol. Surv., 1902.

extreme desert conditions and excessive heights are prohibitive, that semi-arid conditions of varying and precarious intensities lead to nomadic habits, sparse distribution, and limited social and civic evolution, while well-watered plains and fertile valleys, under congenial skies, invite fixed habitation and the development of stable civil and social institutions. Excessive humidity, dense forests, and extreme ruggedness of surface tend to limitation and repression among primitive peoples. Early in the history of the race, it is presumed that a warm climate was more favorable than a severe one. From these considerations and from historical evidence arises the presumption that the primitive centers of evolution of the race were somewhere in the open or diversified parts of the warm tract of the largest of the continents. From this, or from some analogous tract in that quarter of the globe, there seem to have been divergent movements to all habitable lands.

A basal factor in the early evolution of civilization was the productiveness of the soil. The advance from hunting and fishing and herding was dependent essentially on agriculture, and was therefore influenced largely by the fertility of the soil and suitable climatic conditions. Loss of soil-fertility has been one cause which has forced the migration of centers of civilization. In lower latitudes the upland soils are mostly the residue produced by the decomposition of the underlying rocks and not removed by erosion. With cultivation, wash and wind-drift are accelerated, and unless protective measures are employed, as has not been the case usually, the soils are carried away, and barrenness succeeds fertility. There are areas in the Orient, once well settled, where nothing grows except such plants as find a foothold in the crevices of the rock. In some places, soils underlain by sandy subsoils have been washed away, leaving barren wastes. Sands from the exposed subsoil have then been driven by the wind over adjacent fertile tracts, making them barren. The explanation of much of the former richness and present poverty of Oriental peoples no doubt lies in this simple process. Impoverishment of soil threatens many peoples to-day, and is in process of actual realization. This is one of the fields in which conservation is most important.

In glaciated lands the soil-factor has a character quite its own. 1. Near the centers of ice radiation the old soils were worn away, and new soils have not developed in equal amount in their stead. Reduced fertility is the result. These areas lie chiefly in high

latitudes where other factors do not favor human development. 2. In regions of heavy glacial deposition, which fortunately include the greater and the more southerly parts of the glaciated area, a deep sheet of comminuted rock-material, ready for easy conversion into soil by weathering and organic action, covers great plains. Furthermore, the drift has a gentle relief that does not favor rapid erosion. North of the border of the glaciated area in North America, in a belt 400 or 500 miles wide, the subsoil of glacial flour and old soil, glacially mixed, has an average thickness of about 100 feet. A similar statement may be made of a large area in north-central Europe. The average thickness of the residuary soils of unglaciated regions similarly situated is about 5 feet. The twenty-fold provision for permanent fertility thus arising from glaciation seems likely to be a factor of importance in the localization of the basal industry (agriculture) of mankind, and of the phases of civilization that are dependent on it.

With the evolution of the industrial arts, resources which were neglected at first have come to play important parts in the distribution and in the activities of the race, among which are the long and growing lists of mineral resources. Chief among these are the metallic ores, the fossil fuels, the mineral fertilizers, and the structural and ornamental materials of stone and clay. These now influence man's distribution and activities far more than formerly, and they are quite certain to be more influential still in the future.

The distribution and activities of men recently have come to be affected by the distribution of the water-power that arose from the deformations of the late Tertiary periods, and the stream-diversions of the glacial period. With little doubt, such sources of power are to play an increasingly large part in human affairs as time goes on and the stored fuels are exhausted.

With the increasing complexity of human activities, the localization of the race will more and more depend on *combinations of resources and conditions;* but it is difficult to see the time when persistent fertility of the soil, under favorable climatic conditions, co-ordinated with great supplies of fuels, ores, and structural materials, will not constitute a decisive and controlling advantage.

**Provincialism giving place to cosmopolitanism.** The early history of human dispersal was marked by pronounced provincialism. Early peoples were much isolated by distance and by natural barriers, and they often interposed artificial barriers against free

intercommunication, and hence against the development of a common cosmopolitan type. So long as hunting and fishing were the dominant pursuits, a wider and wider dispersion into small tribes was a necessary tendency. That such artificial sources of provincialism were more effective than natural ones seems to be implied by the fact that while physiological differences sufficiently marked readily to characterize varieties are numbered by hundreds, dialects sufficiently different to prevent free intercourse are numbered by thousands. Provincial sentiment to-day manifests itself more conspicuously in language than in most other ways.

When efficient water-transportation was developed and the control of the sea attained, a period of cosmopolitan tendency was inaugurated. This has been greatly accelerated in the last few decades, supplemented by rapid land-transportation and electric communication, and is rapidly involving the whole race in a cosmopolitan movement. Almost the whole world is already in daily communication, and most races are more or less habitually intermingling by travel and trade. That this is to become more and more habitual until the whole race shall be in constant intercommunication, is not to be questioned. There will then have been inaugurated the most marked period of cosmopolitanism, in all senses of the term, which the world has ever witnessed. What all this will ultimately mean for the race we do not venture to predict.

**Man as a geological agency.** The earlier geologists were inclined to regard man's agency in geological progress as rather trivial, perhaps because physiographic geology, in which his influence is felt chiefly, was then less studied than other phases with which he has little to do. The fact probably is that no previous agent, in an equal period of time, has so greatly influenced the life of the land, or the rate of land-degradation, as man has since the agricultural epoch was well established. That this influence will be increased during coming centuries seems clear. The flora is rapidly passing from that which had been evolved by natural agencies through the ages, to that which man selects for cultivation or preservation. With the further progress of this movement, native floras seem destined to early extinction. The same may be said of native faunas. Favored animals, under man's care, flourish beyond precedent, while others, so far as they are within his reach, are suffering rapid declines that look toward extinction.

Life in the sea is less profoundly affected than that on the land, but even that does not escape modification. The most pronounced exceptions to man's dominance, and those that bid fair to contest his supremacy longest, are found in organisms too minute to be controlled easily by him, and in organisms that, quite against his will, flourish on the conditions he furnishes. But even the accelerated evolution of these organisms is a part of the profound biological revolution which attends man's dominance.

Man's control has not thus far been characterized by much recognition of the complicated interrelations of organisms and of the consequences of disturbing the balance in the organic kingdom, and he is reaping, and is certain to reap more abundantly, the unfortunate fruits of ignorant and careless action. For the most part, man has been guided by immediate considerations, and even these not always controlled by much intelligence. Thus great wantonness has attended his destruction of both plant and animal life. But a more intelligent as well as a more sympathetic attitude is developing, and will doubtless soon become dominant. A new era in control and selection is dawning. New varieties and races are being produced that not only depart widely from the parent stock, but diverge in lines chosen to meet given conditions, or to produce desired products. How far this may yet go it is impossible now to predict.

**Prognostic geology.** The long perspective of the past should afford at least some suggestions of the future, but it must be confessed that the most important conjectures as to the future are dependent on interpretations of the past that are not yet certain. A word has been said relative to a possible return of a glacial epoch, but no sure prediction can be made. Question has been raised as to whether the deformations of recent times are over, but the answer remains uncertain. The duration of the earth as a habitable globe has been a common theme of prognosis. A final refrigeration as the result of the cooling of a once molten globe has been the usual forecast, and the final doom of the race has been a favorite theme for pseudo-scientific romances. But this all hangs on the doctrine of a former molten earth, if not on the doctrine of its origin from a gaseous nebula. Under the alternative conception of a slow-grown earth conserving its energies, conjoined with a more generous conception of the energies resident in the sun and the stellar system, no narrow limit need be assigned to the habitability of the earth. A Psycho-

zoic era, as long as the Cenozoic or the Paleozoic, or an eon as long as the cosmic and the biotic ones, may quite as well be predicted as anything less. The forecast is at best speculative, but an optimistic outlook seems more likely to prove true than a pessimistic one. An immeasurably higher evolution than that now reached, with attainments beyond present comprehension, is a reasonable hope.

The forecast of an eon of intellectual and spiritual development comparable in magnitude to the prolonged physical and biotic evolutions lends to the total view of earth-history great moral satisfaction, and the thought that individual contributions to the higher welfare of the race may realize their fullest fruits by continued influence through scarcely limited ages, gives value to life and inspiration to personal endeavor.

# APPENDIX

## REFERENCE TABLE OF THE PRINCIPAL GROUPS OF PLANTS.

| | | | |
|---|---|---|---|
| THALLOPHYTES (Thallus plants) | Algæ and algoid forms | Diatomaceæ, diatoms. | |
| | | Coccospheres | Pelagic algæ. |
| | | Rhabdospheres | |
| | | Cyanophyceæ, blue-green algæ. | |
| | | Chlorophyceæ, green algæ, including stoneworts. | True algæ. |
| | | Rhodophyceæ, red algæ. | |
| | | Phæophyceæ, brown algæ. | |
| | Fungi and fungoid forms | Myxomycetes, "animal fungi," slime-molds. | |
| | | Schizomycetes, "fission-fungi," bacteria. | |
| | | Phycomycetes, algæ-fungi, water-molds. | |
| | | Ascomycetes, ascus-fungi, mildews. | |
| | | Basidiomycetes, basidium-fungi, smuts, rusts, mushrooms. | |
| | Lichens | Symbiont algæ and fungi. | |
| BRYOPHYTES (Moss plants) | Hepaticæ, liverworts. | | |
| | Musci, mosses. | | |
| PTERIDOPHYTES (Fern plants) | Lycopodiales. | Lepidodendra, sigillarias, club-mosses. | |
| | Sphenophyllales. | | |
| | Equisetales | Calamites. | |
| | | Equisetæ, scouring-rushes, horse-tails. | |
| | Filicales | Filices, true ferns. | |
| SPERMATOPHYTES (Seed plants) | Gymnospermæ (naked seed) | Cycadofilicales. | |
| | | Bennettitales. | |
| | | Cycadales. | |
| | | Cordaitales. | |
| | | Ginkgoales. | |
| | | Coniferales. | |
| | | Gnetales. | |
| | Angiospermæ (covered seed) (Flowering plants) | Dicotyledoneæ. Most common forest trees (except conifers), most shrubs and most netted-veined leaved herbs. | |
| | | Monocotyledoneæ, cereals, grasses, etc. | |

## REFERENCE TABLE OF THE PRINCIPAL GROUPS OF ANIMALS[1]

| | | | |
|---|---|---|---|
| PROTOZOA (the simplest animals) | | Rhizopoda | Foraminifera. Radiolaria. |
| PROTOZOA (the simplest animals) | | Flagellata | Unknown in fossil state. |
| PROTOZOA (the simplest animals) | | Infusoria | Unknown in fossil state. |
| PROTOZOA (the simplest animals) | | Gregarina | Unknown in fossil state. |
| COELENTERATA (Sponges, corals, jellyfishes) | Porifera | Spongiæ | Calcareous sponges. Siliceous sponges. |
| COELENTERATA (Sponges, corals, jellyfishes) | Cnidaria | Anthozoa, coral polyps. | |
| COELENTERATA (Sponges, corals, jellyfishes) | Cnidaria | Hydrozoa, hydroids and medusæ. | |
| ECHINODERMATA (Crinoids, starfishes, sea-urchins) | Pelmatozoa | Cystoidea, cystids. | |
| ECHINODERMATA (Crinoids, starfishes, sea-urchins) | Pelmatozoa | Crinoidea, stone lilies. | |
| ECHINODERMATA (Crinoids, starfishes, sea-urchins) | Pelmatozoa | Blastoidea, blastoids. | |
| ECHINODERMATA (Crinoids, starfishes, sea-urchins) | Asterozoa | Ophiuroidea, brittle-stars. | |
| ECHINODERMATA (Crinoids, starfishes, sea-urchins) | Asterozoa | Asteroidea, starfishes. | |
| ECHINODERMATA (Crinoids, starfishes, sea-urchins) | Echinozoa | Echinoidea, sea-urchins. | |
| ECHINODERMATA (Crinoids, starfishes, sea-urchins) | Echinozoa | Holothuroidea, sea-cucumbers. | |
| VERMES (Worms) | | Platyhelminthes | Rare as fossils. |
| VERMES (Worms) | | Rotifera | Rare as fossils. |
| VERMES (Worms) | | Nemathelminthes | Rare as fossils. |
| VERMES (Worms) | | Gephyrea | Rare as fossils. |
| VERMES (Worms) | | Annelida, sea-worms. | |
| MOLLUSCOIDEA (Mollusc-like forms) | | Bryozoa, sea-mosses. | |
| MOLLUSCOIDEA (Mollusc-like forms) | | Brachiopoda, lamp-shells. | |
| MOLLUSCA (Molluscs) | | Pelecypoda, lamellibranches, bivalves. | |
| MOLLUSCA (Molluscs) | | Scaphopoda, tusk-shells. | |
| MOLLUSCA (Molluscs) | | Amphineura, chiton. | |
| MOLLUSCA (Molluscs) | | Gastropoda, univalves, snails, etc. | |
| MOLLUSCA (Molluscs) | | Cephalopoda, nautilus, cuttlefish. | |
| ARTHROPODA (The articulates) | Branchiata | Crustacea. | |
| ARTHROPODA (The articulates) | Branchiata | Trilobita, trilobites. | |
| ARTHROPODA (The articulates) | Branchiata | Gigantostraca, horseshoe crabs. | |
| ARTHROPODA (The articulates) | Branchiata | Entomostraca, ostracoids, barnacles. | |
| ARTHROPODA (The articulates) | Branchiata | Malacostraca, lobsters, crabs. | |
| ARTHROPODA (The articulates) | Tracheata | Myriapoda, centipedes. | |
| ARTHROPODA (The articulates) | Tracheata | Arachnoidea, spiders, scorpions. | |
| ARTHROPODA (The articulates) | Tracheata | Insecta, insects. | |
| VERTEBRATA | | Cyclostomata, lampreys. | |
| VERTEBRATA | | Pisces (fishes) | Selachii, sharks. |
| VERTEBRATA | | Pisces (fishes) | Holocephali, spook-fishes. |
| VERTEBRATA | | Pisces (fishes) | Dipnoi, lung-fishes. |
| VERTEBRATA | | Pisces (fishes) | Teleostomi, ganoids and teleosts (common fishes). |
| VERTEBRATA | | Amphibia, amphibians, batrachians. | |
| VERTEBRATA | | Reptilia, reptiles. | |
| VERTEBRATA | | Aves, birds. | |
| VERTEBRATA | | Mammalia (mammals) | Prototheria, monotremes. |
| VERTEBRATA | | Mammalia (mammals) | Metatheria, marsupials. |
| VERTEBRATA | | Mammalia (mammals) | Eutheria, placentals. |

[1] After Zittel in the main.

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